Principles of Programming
(4190.306)

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Syllabus

- Lecture & Practice Session
  - Tue: 15:30 ~ 16:20 & 18:30 ~ 20:20
  - Thu: 15:30 ~ 16:20 (302-209)
  - https://github.com/snu-sf-class/pp201902
  - Bring your laptop to lectures & practice sessions
- Instructor
  - Chung-Kil Hur
  - http://sf.snu.ac.kr/gil.hur/
- Teaching Assistant
  - Yonghyun Kim, Dongjoo Kim.
    Contact TAs at pp2019fall@sf.snu.ac.kr
- Grading (tentative)
  - Attendance: 5%, Assignments: 25%
  - Midterm exam: 30%, Final exam: 40%

Free Laptop Rental

You can rent a laptop from the department for free.

Who am I?

➢ Prof. Chung-Kil (Gil) Hur   [허충길]
- Education: KAIST (B.S.), Univ of Cambridge (Ph.D.)
- Software Foundations Lab
  http://sf.snu.ac.kr
- Research Topics
  - Software Verification
  - Low-level Language Semantics (C/C++/LLVM/Rust)
  - Relaxed-Memory Concurrency
- Our collaborators
  - [UK] U of Cambridge, Microsoft Research Cambridge
  - [Germany] Max Planck Institute for Software Systems
  - [France] INRIA
  - [USA] Princeton, Yale, Upenn, Utah, Google, IBM, Mozilla.
- Publications
  - 11 top conference papers (last 6 years at SNU).
    PLDI(6),POPL(2),OOPSLA(1),ICFP(1),AAAI(1)
- (High school) Bronze medal in IMO 1994.

Introduction

Overview

➢Part 1
Functional Programming with Function Applications

➢Part 2
Object-Oriented Programming

➢Part 3
Type Classes for Specifications

➢Part 4
Imperative Programming with Memory Updates

Imperative vs. Functional Programming

➢Imperative Programming
  • Computation by memory reads/writes
  • Sequence of read/write operations
  • Repetition by loop
  • More procedural
  • Easier to write efficient code

```
sum = 0;
i = n;
while (i > 0) {
    sum = sum + i;
    i = i - 1;
}
```

➢Functional Programming
  • Computation by function application
  • Composition of function applications
  • Repetition by recursion
  • More declarative
  • Easier to write safe code

```
def sum(n) =
    if (n <= 0)
        0
    else
        n + sum(n-1)
```

Both Imperative & Functional Style Supported

➢Many languages support both imperative & functional style
- More imperative: Java, Javascript, C++, Python, Rust, …
- More functional: OCaml, SML, Lisp, Scheme, …
- Middle: Scala
- Purely functional: Haskell (monadic programming)

Object-Oriented Programming

➤Object-Oriented Programming
- Classes/Objects: data + methods
- Can separate Specification & Implementation

```
class Point(x: Int, y: Int) {
  // data
  val px : Int = x
  val py : Int = y
  // methods
  def plus(q : Point) : Point =
    new Point(px + q.px, py + q.py)
}
val p1 : Point = new Point(3,4)
val p2 : Point = new Point(1,10)
val p3 : Point = p1.plus(p2)
```

Why Scala?

➢Why Scala?
- Equally well support both imperative & functional style
- Many advanced features (both OOP & Type class supported)
- Compatible with Java

PART 1
Functional Programming with Function Applications

Names, Functions and Evaluations

Values, Expressions, Names

➢ Types and Values
  - A type is a set of values
  - `Int`: {-2147483648,…,-1,0,1, …,2147483647} //32-bit integers
  - `Double`: 64-bit floating point numbers // real numbers in practice
  - `Boolean`: {true, false}
  - …

➢ Expressions
  - Composition of
    values, names, primitive operations, …

➢ Name Binding
  - Binding expressions to names

➢ Examples
```
def a = 1 + (2 + 3)
def b = 3 + a * 4
```

Evaluation

➢Evaluation
- Reducing an expression into a value
- Strategy
1. Take a name or an operator (outer to inner)
2. (name) Replace the name with its associated expression
3. (name) Evaluate the expression
4. (operator) Evaluate its operands (left to right)
5. (operator) Apply the operator to its operands

➢Examples
```
5+b ~ 5+(3+a*4) ~ 5+(3+(1+(2+3))*4) ~ … ~ 32
```

Functions and Substitution

➤Functions
  • Expressions with Parameters
  • Binding functions to names

```
def f(x: Int): Int = x + a
```

➤Evaluation by substitution
  • …
  • (function) Evaluate its operands (left to right)
  • (function)
    Replace the function application by the expression of the function
    Replace its parameters with the operands

```
5+f(f(3)+1) ~ 5+f((3+a)+1) ~ … ~ 5+f(10) ~ 5+(10+a)
~ … ~ 21
```

Simple Recursion

➢Recursion
- Use X in the definition of X
- Powerful mechanism for repetition
- Nothing special but just rewriting

```
def sum(n: Int) : Int =
   if (n <= 0)
      0
   else
      n + sum(n-1)

sum(2) ~ if (2<=0) 0 else (2+sum(2-1)) ~
2+sum(1) ~ 2+(if (1<=0) 0 else (1+sum(1-1))) ~
2+(1+sum(0)) ~ 2+(1+(if (0<=0) 0 else (0+sum(0-1)))) 
~ 2+(1+0) ~ 3
```

Termination/Divergence

Evaluation may not terminate

➢Termination
- An expression may reduce to a value

➢Divergence
- An expression may reduce forever

```
def loop: Int = loop

loop ~ loop ~ loop ~ …
```

Evaluation strategy: Call-by-value, Call-by-name

$$f(e1,e2)$$

➢Call-by-value
  • Evaluate the arguments first, then apply the function to them
➢Call-by-name
  • Just apply the function to its arguments, without evaluating them.

```
def square (x: Int) = x * x

[cbv]square(1+1) ~ square(2) ~ 2*2 ~ 4

[cbn]square(1+1) ~ (1+1)*(1+1) ~ 2*(1+1) ~ 2*2 ~ 4
```

CBV, CBN: Differences

➢Call-by-value
- Evaluates arguments once

➢Call-by-name
- Do not evaluate unused arguments

➢Question
- Do both always result in the same value?

Scala's evaluation strategy

➢Call-by-value
  • By default
➢Call-by-name
  • Use "=>"

```scala
def one(x: Int, y: =>Int) = 1

one(1+2, loop)

one(loop, 1+2)
```

Scala's name binding strategy

➢ Call-by-value
- Use "val" (also called "field")   e.g. `val x = e`
- Evaluate the expression first, then bind the name to it

➢ Call-by-name
- Use "def" (also called "method")   e.g. `def x = e`
- Just bind the name to the expression, without evaluating it
- Mostly used to define functions

```scala
def a = 1 + 2 + 3
val a = 1 + 2 + 3 // 6
def b = loop
val b = loop

def f(a: Int, b: Int): Int = a*b - 2
```

Conditional Expressions

➢If-else
- if (b) e_1 else e_2
- b : Boolean expression
- e_1, e_2: expressions of the same type

➢Rewrite rules:
- if (true) e_1 else e_2 → e_1
- if (false) e_1 else e_2 → e_2

```scala
def abs(x: Int) = if (x >= 0) x else -x
```

Boolean Expressions

➢Boolean expression
- `true, false`
- `!b`
- `b && b`
- `b || b`
- `e <= e, e >= e, e < e, e > e, e == e, e != e`

➢Rewrite rules:
- `!true → false`
- `!false → true`
- `true && b → b`
- `false && b → false`
- `true || b → true`
- `false || b → b`

`true && (loop == 1) ~ loop == 1 ~ loop == 1`

Exercise: and, or

➢ Write two functions
  - `and(x,y) == x && y`
  - `or(x,y) == x || y`
  - Do not use `&&,||`

```
and(false,loop==1)
~ if (false) loop==1 else false
~ false

and(true,loop==1)
~ if (true) loop==1 else false
~ loop==1 ~ loop==1 …
```

Solution

```scala
def and(x: Boolean, y: =>Boolean) =
  if (x) y else false

def or(x: Boolean, y: =>Boolean) =
  if (x) true else y
```

Exercise: square root calculation

➢Calculate square roots with Newton's method

```scala
def isGoodEnough(guess: Double, x: Double) =
  ??? // guess*guess is 99.9% close to x

def improve(guess: Double, x: Double) =
  (guess + x/guess) / 2

def sqrtIter(guess: Double, x: Double): Double =
  ??? // repeat improving guess until it is good enough

def sqrt(x: Double) =
  sqrtIter(1, x)

sqrt(2)
```

Solution

➢Calculate square roots with Newton's method

```scala
def isGoodEnough(guess: Double, x: Double) =
  guess*guess/x > 0.999 && guess*guess/x < 1.001

def improve(guess: Double, x: Double) =
  (guess + x/guess) / 2

def sqrtIter(guess: Double, x: Double): Double =
  if (isGoodEnough(guess,x)) guess
  else sqrtIter(improve(guess,x),x)

def sqrt(x: Double) =
  sqrtIter(1, x)

sqrt(2)
```

Blocks and Name Scoping

Blocks in Scala

➤ Block
- ```
  { val x1 = e1
    def x2 = e2
    e
  }
  ```
- Is an expression
- Allow nested name binding
- Allow arbitrary order of "def"s, but not "val"s (think about why)

Scope of names

➢Block

```scala
val t = 0
def f(x: Int) = t + g(x)
def g(x: Int) = x * x
val x = f(5)
val r = {
  val t = 10
  val s = f(5)
  s - t
}
t + r
```

- A definition inside a block is only accessible within the block
- A definition inside a block shadows definitions of the same name outside the block
- A definition is accessible inside a nested block unless it is shadowed
- A function is evaluated under the environment where it is defined, not the environment where it is invoked.

Rewriting for Blocks

```
1: val t = 0              5: val r = {
2: def f(x: Int) = t + g(x)    6:   val t = 10
3: def g(x: Int) = x*x         7:   val s = f(5)
4: val x = f(5)                8:   s - t }
                               9: t + r
```

➢Evaluation with Environment

[],1 ~ [t=0],2 ~ [...,f=(x)t+g(x)],3 ~ [...,g=(x)x*x],4
~ [...,x=25],5 ~ [...]:[],6 ~ [...]:[t=10],7
~ [...]:[...,s=25],8 ~ [...,r=15],9 ~ [...],15

```
4: [t=0,f=...,g=...]:[x=5],t+g(x) ~ 0+g(5) ~ 25
    g(5): [t=0,f=...,g=...]:[x=5],x*x ~ 5*5 ~ 25

7: [t=0,f=...,g=...,x=25]:[x=5],t+g(x) ~ 0+g(5) ~ 25
    g(5): [t=0,f=...,g=...,x=25]:[x=5],x*x ~ 5*5 ~ 25
```

Note: The same name cannot be defined twice in the same block

Example: def with no arguments

```
1: val t = 0
2: def x = t+t      // is treated as def x() = t
3: val r = {
4:    val t = 10
5:    x }           // is treated as x()
```

➢Evaluation with Environment

[],1 ~ [t=0],2 ~ […,x=()t+t],3 ~ […]:[],4

~ […]:[t=10],5 ~ […,r=0],6

  5: [t=0,x=()t+t]:[],t+t ~ 0

Semi-colons and Parenthesis

➢Block
- Can write two definitions/expressions in a single line using ;
- Can write one definition/expression in two lines using (), but can omit () when clear

```
// ok
val r = {
  val t = 10; val s = square(5); t +
  s }
// Not ok
val r = {
  val t = 10; val s = square(5); t
  + s }
// ok
val r = {
  val t = 10; val s = square(5); (t
  + s) }
```

Exercise: Writing Better Code using Blocks

➢Make the following code better

```scala
def isGoodEnough(guess: Double, x: Double) =
  guess*guess/x > 0.999 && guess*guess/x < 1.001

def improve(guess: Double, x: Double) =
  (guess + x/guess) / 2

def sqrtIter(guess: Double, x: Double): Double = {
  if (isGoodEnough(guess,x)) guess
  else sqrtIter(improve(guess,x),x)
}

def sqrt(x: Double) =
  sqrtIter(1, x)

sqrt(2)
```

Solution

```scala
def sqrt(x: Double) = {
  def sqrtIter(guess: Double, x: Double): Double = {
    if (isGoodEnough(guess,x)) guess
    else sqrtIter(improve(guess,x),x)
  }
  def isGoodEnough(guess: Double, x: Double) = {
    val ratio = guess * guess / x
    ratio > 0.999 && ratio < 1.001
  }
  def improve(guess: Double, x: Double) =
    (guess + x/guess) / 2

  sqrtIter(1, x)
}

sqrt(2)
```

Lazy Call-By-Value

Lazy call-by-value

➢Lazy call-by-value
  • Use "lazy val"   e.g. `lazy val x = e`
  • Evaluate the expression first time it is used, then bind the name to it

```
def f(c: Boolean, i: =>Int): Int = {
    lazy val iv = i
    if (c) 0
    else   iv * iv * iv
}

f(true, {println("ok"); 100+100+100+100})
f(false, {println("ok"); 100+100+100+100})
```

Tail Recursion

Recursion needs care

➢Summation function

- Write a summation function `sum` such that
  ```
  sum(n) = 1+2+…+n
  ```

- Test
  ```
  sum(10),sum(100),sum(1000),sum(10000),
  sum(100000), sum(1000000)
  ```

- What's wrong? (Think about evaluation)

Recursion: Try

```
def sum(n: Int): Int =
  if (n <= 0) 0 else (n+sum(n-1))
```

Recursion: Tail Recursion

```scala
import scala.annotation.tailrec

def sum(n: Int): Int = {
  @tailrec def sumItr(res: Int, m: Int): Int =
    if (m <= 0) res else sumItr(m+res,m-1)
  sumItr(0,n)
}
```

Higher-Order Functions

Functions as Values

➢Functions
- Functions are normal values of function types $(A_1,\ldots,A_n =\!\!> B)$.
- They can be copied, passed and returned.
- Functions that take functions as arguments or return functions are called higher-order functions.
- Higher-order functions increase code reusability.

Examples

```scala
def sumLinear(n: Int): Int =
  if (n <= 0) 0 else n + sumLinear(n-1)

def sumSquare(n: Int): Int =
  if (n <= 0) 0 else n*n + sumSquare(n-1)

def sumCubes(n: Int): Int =
  if (n <= 0) 0 else n*n*n + sumCubes(n-1)
```

Q: How to write reusable code?

Examples

```scala
def sum(f: Int=>Int, n: Int): Int =
  if (n <= 0) 0 else f(n) + sum(f, n-1)

def linear(n: Int) = n
def square(n: Int) = n * n
def cube(n: Int) = n * n * n

def sumLinear(n: Int) = sum(linear, n)
def sumSquare(n: Int) = sum(square, n)
def sumCubes(n: Int) = sum(cube, n)
```

Anonymous Functions

➢ Anonymous Functions

- Syntax
  $(x_1: T_1,...,x_n:T_n) \Rightarrow e$
  or
  $(x_1,...,x_n) \Rightarrow e$

```
def sumLinear(n: Int) = sum((x:Int)=>x, n)
def sumSquare(n: Int) = sum((x:Int)=>x*x, n)
def sumCubes(n: Int) = sum((x:Int)=>x*x*x, n)
```

Or simply

```
def sumLinear(n: Int) = sum((x)=>x, n)
def sumSquare(n: Int) = sum((x)=>x*x, n)
def sumCubes(n: Int) = sum((x)=>x*x*x, n)
```

Exercise

```scala
def sum(f: Int=>Int, a: Int, b: Int): Int =
  if (a <= b) f(a) + sum(f, a+1, b) else 0

def product(f: Int=>Int, a: Int, b: Int): Int =
  if (a <= b) f(a) * product(f, a+1, b) else 1
```

DRY (Do not Repeat Yourself) using a higher-order function, called "mapReduce".

Exercise

```scala
def mapReduce(reduce: (Int,Int)=>Int,inival: Int,
              f: Int=>Int, a: Int, b: Int): Int = {
  if (a <= b) reduce(f(a),mapReduce(reduce,inival,f,a+1,b))
  else inival
}

def sum(f: Int=>Int, a: Int, b: Int): Int =
  mapReduce((x,y)=>x+y,0,f,a,b)

def product(f: Int=>Int, a: Int, b: Int): Int =
  mapReduce((x,y)=>x*y,1,f,a,b)
```

Closures for functional values

```
1:  val t = 0
2:  val f : Int=>Int = {        // Note: What if using "def f"?
3:      val t = 10
4:      def g(x: Int) : Int = x + t
5:      g _ }
6:  f(20)
```

* Try: Evaluation without Closures

[],1 ~ [t=0],2 ~ […]:[],3 ~ […]:[t=10],4

~ […]:[…,g=(x)x+t],5 ~ [t=0,f=(x)x+t],6 ~ […],20

  6: [t=0,f=(x)x+t]:[x=20],x+t ~ 20+0 ~ 20

* Evaluation with Closures

E1[],1 ~ E1[t=0],2 ~ E1[…]:E2[],3 ~ E1[…]:E2[t=10],4

~ E1[…]:E2[t=10,g=(x)x+t],5

~ E1[t=0,f=((x)x+t,E2)],6 ~ E1[…],30

  6: E1:E2:E3[x=20],x+t ~ 20+10 ~ 30

Problem

```
// should be allowed
{
  def f(x:Int) = g(x)
  def g(x: Int) = 10
  val x = f(10)
  x
}


// should not be allowed
{
  def f(x:Int) = g(x)
  val x = f(10)
  def g(x: Int) = 10
  x
}
```

Safety Checking

Safety checking for ruling out accessing undefined values is simple.

- For "val x = e",
  all names in "e" should be defined before this definition.

- For "def x = e",
  all names in "e" should be defined before the next "val" definition.

```
/* The following code passes the safety checking */
{ def f(x:Int) = g(x)
  def g(x: Int) = 10
  val a = 10
  f(10) }
/* The following code fails at the safety checking */
{ def f(x:Int) = g(x)
  val a = 10
  def g(x: Int) = 10
  f(10) }
```

(Parameterized) code vs. values

- Functions defined using "def" are not values but parameterized code/expressions.
- Anonymous functions are values.
- Code `f` is converted to a value `(f _)`.
- The compiler often infers and inserts missing conversions automatically.
- Anonymous functions can be seen as syntactic sugar:

  `(x:T)=>e`

  is equivalent to

  `{ def noname(x:T) = e; (noname _) }`

  where `noname` is not used in `e`.
- One can even write a recursive anonymous function in this way.
- Q: what's the difference between param. exps and function values?
  A: function values are "closures" (ie, param. exp. + env.)
- Q: how to implement call-by-name?
  A: The argument expression is converted to a closure.

Example: call by name with closures

```
1: val t = 0
2: def f(x: =>Int) = t + x
3: val r = {
4:    val t = 10
5:   f(t*t) }              // t*t is treated as ()=>t*t
```

➢Evaluation with Closures

```
E1[],1 ~ E1[t=0],2 ~ E1[t=0,f=(x:=>Int)t+x],3
~ E1[…]:E2[],4 ~ E1[…]:E2[t=10],5 ~ E1[…,r=100],6

  5: E1:E3[x=(()t*t,E2)],t+x
       ~ 0 + x ~ 0 + 100 ~ 100
  x: E1:E2,t*t ~ 10*10 ~ 100
```

Currying

Motivation

```
def sum(f: Int=>Int, a: Int, b: Int): Int =
  if (a <= b) f(a) + sum(f, a+1, b) else 0
def linear(n: Int) = n
def square(n: Int) = n * n
def cube(n: Int) = n * n * n
def sumLinear(a: Int, b: Int) = sum(linear, a, b)
def sumSquare(a: Int, b: Int) = sum(square, a, b)
def sumCubes(a: Int, b: Int) = sum(cube, a, b)
```

We want the following. How?

```
def sumLinear = sum(linear)
def sumSquare = sum(square)
def sumCubes = sum(cube)
```

Solution

```scala
def sum(f: Int=>Int): (Int,Int)=>Int = {
  def sumF(a: Int, b: Int): Int =
    if (a <= b) f(a) + sumF(a+1, b) else 0
  sumF
}

def sumLinear = sum(linear)
def sumSquare = sum(square)
def sumCubes = sum(cube)
```

Benefits

```
def sumLinear = sum(linear)
def sumSquare = sum(square)
def sumCubes = sum(cube)


sumSquare(3,10) + sumCubes(5,20)
```

We don't need to define the wrapper functions.

```
sum(square)(3,10) + sum(cube)(5,20)
```

Multiple Parameter List

```scala
def sum(f: Int=>Int): (Int,Int)=>Int = {
  def sumF(a: Int, b: Int): Int =
    if (a <= b) f(a) + sumF(a+1, b) else 0
  sumF _
}
```

Or simply:
```scala
def sum(f: Int=>Int)(a: Int, b: Int): Int =
  if (a <= b) f(a) + sum(f)(a+1, b) else 0
```

Note that sum(f) is just code.
(sum(f) _) creates a closure like (sumF _)

The following code is inefficient. Think about why.
```scala
def sum(f: Int=>Int): (Int,Int)=>Int =
  (a,b) => if (a <= b) f(a) + sum(f)(a+1, b) else 0
```

Currying and Uncurrying

- A function of type

$$(T_1, T_2, \ldots, T_n) \Rightarrow T$$

  can be turned into that of type

$$T_1 \Rightarrow (T_2 \Rightarrow (\ldots \Rightarrow (T_n \Rightarrow T) \ldots))$$

- This is called "currying" named after Haskell Brooks Curry.
- The opposite direction is called "uncurrying".

Currying using Anonymous Functions

```scala
def foo(x: Int, y: Int, z: Int)(a: Int, b: Int) =
  x + y + z + a + b

val f1 = (x: Int, z: Int, b: Int)=> foo(x,1,z)(2,b)

val f2 = foo(_:Int,1,_:Int)(2, _:Int)

val f3 = (x: Int, z: Int) => ((b: Int) => foo(x,1,z)(2,b))

f1(1,2,3)
f2(1,2,3)
f3(1,2)(3)
```

Exercise

Curry the mapReduce function.

```
def mapReduce(reduce: (Int,Int)=>Int,inival: Int,
              f: Int=>Int, a: Int, b: Int): Int = {
  if (a <= b) reduce(f(a),mapReduce(reduce,inival,f,a+1,b))
  else inival
}

def sum(f: Int=>Int, a: Int, b: Int): Int =
  mapReduce((x,y)=>x+y,0,f,a,b)

def product(f: Int=>Int, a: Int, b: Int): Int =
  mapReduce((x,y)=>x*y,1,f,a,b)
```

Solution

```
def mapReduce(reduce:(Int,Int)=>Int,inival: Int)
            (f: Int=>Int) (a: Int, b: Int): Int = {
  if (a <= b) reduce(f(a),mapReduce(reduce,inival)(f)(a+1,b))
  else inival
}

// need to make a closure since mapReduce is param. code.
def sum = mapReduce((x,y)=>x+y,0) _

// val is better than def. Think about why.
val product = mapReduce((x,y)=>x*y,1) _
```

Exceptions

Exception & Handling

```scala
class factRangeException(val arg: Int) extends Exception

def fact(n : Int): Int =
  if (n < 0) throw new factRangeException(n)
   else if (n == 0) 1
   else n * fact(n-1)

def foo(n: Int) = fact(n + 10)

try {
  println (fact(3))
  println (foo(-100))
} catch {
  case e : factRangeException => {
    println("fact range error: " + e.arg)
  }
}
```

Datatypes

Types so far

Types have introduction operations and elimination ones.
- Introduction: how to construct elements of the type
- Elimination: how to use elements of the type

➢ Primitive types
  - Int, Boolean, Double, String, …
  - Intro for Int: …,-2,-1,0,1,2,
  - Elim for Int: +,-,*,/,<,<=,…

➢ Function types
  - Int=>Int, (Int=>Int)=>(Int=>Int), …
  - Intro: (x:T)=>e
  - Elim: f(v)

Tuples

➢ Tuples

Intro:
- (1,2,3) : (Int, Int, Int)
- (1,"a"): (Int, String)

Elim:
- (1, "a",10)._1 = 1
- (1, "a",10)._2 = "a"
- (1, "a",10)._3 = 10

Only up to length 22

Structural Types (a.k.a. Record Types): Examples

```
def bar (x: Int) = x+1
val foo = new //or, object foo
{ val a = 1+2
  def b = a + 1
  def f(x: Int) = b + x
  def f(x: String) = "hello" + x
  val g : Int => Int = bar _
}
foo.b
foo.f(3)
foo.f("gil")
def g(x: {val a: Int; def b: Int;
          def f(x:Int): Int; def f(x:String): String,
          val g: Int => Int}) =
  x.f(3)
g(foo)
```

Structural Types: Evaluation

```
1: def bar (x: Int) = x+1
2: val foo = new //or, object foo
3: { val a = 2 + 1
4:    def f(x: Int) = a + x
5:    val g : Int => Int = bar _
6: }
7: val b = foo.f(1)
8: foo.g(b)
```

➢Evaluation with Closures

```
E1[],1 ~ E1[bar=(x)x+1],2 ~ E1[…]:E2[],3 ~
E1[…]:E2[a=3],4 ~
E1[…]:E2[a=3,f=(x)a+x],5 ~
E1[…]:E2[a=3,f=(x)a+x,g=((x)x+1,E1)],6 ~
E1[bar=(x)x+1,foo=(E2)],7 ~
E1[bar=(x)x+1,foo=(E2),b=4],8 ~ 5
7: E1:E2:E3[x=1],a+x ~ 3+1 ~ 4
8: E1:E4[x=4],x+1 ~ 4+1 ~ 5
```

Type Alias

```
val gn = 0
object foo {
  val a = 3
  def b = a + 1
  def f(x: Int) = b + x + gn
}

foo.f(3)

type Foo = {val a: Int; def b: Int; def f(x:Int):Int}

def g(x: Foo) = {
  val gn = 10
  x.f(3)
}

g(foo)
```

Algebraic Datatypes

➢ Ideas
- T = C of T * … * T
  | C of T * … * T
  | …
  | C of T * … * T

- E.g.
  Attr = Name of String
        | Age of Int
        | DOB of Int * Int * Int
        | Height of Double
  Intro:
    Name("Chulsoo Kim"), Name("Younghee Lee"), Age(16),
    DOB(2000,3,10), Height(171.5), …

Algebraic Datatypes: Recursion

➢ Recursive ADT

• E.g.
ILIst = INil
      | ICons of Int * IList

Intro:
  INil(),
  ICons(3, INil()),
  ICons(2, ICons(3, INil())),
  ICons(1, ICons(2, ICons(3, INil()))),
  …

Algebraic Datatypes In Scala

➢Attr

```scala
sealed abstract class Attr
case class Name(name: String) extends Attr
case class Age(age: Int) extends Attr
case class DOB(year: Int, month: Int, day: Int) extends Attr
case class Height(height: Double) extends Attr

val a : Attr = Name("Chulsoo Kim")
val b : Attr = DOB(2000,3,10)
```

➢IList

```scala
sealed abstract class IList
case class INil() extends IList
case class ICons(hd: Int, tl: IList) extends IList

val x : IList = ICons(2, ICons(1, INil()))
def gen(n: Int) : IList =
  if (n <= 0) INil()
  else ICons(n, gen(n-1))
```

Exercise

IOption = INone
      | ISome of Int

BTree = Leaf
    | Node of Int * BTree * BTree

```scala
sealed abstract class IList
case class INil() extends IList
case class ICons(hd: Int, tl: IList) extends IList

def x : IList = ICons(2, ICons(1, INil()))
```

Solution

```
sealed abstract class IOption
case class INone() extends IOption
case class ISome(some: Int) extends IOption

sealed abstract class BTree
case class Leaf() extends BTree
case class Node(value: Int, left: BTree, right: BTree)
    extends BTree
```

Pattern Matching

➢ Pattern Matching
  • A way to use algebraic datatypes

```
e match {
  case C1(…) => e1

   …

  case Cn(…) => en
}
```

Pattern Matching: An Example

```
def length(xs: IList) : Int =
  xs match {
    case INil() => 0
    case ICons(x, tl) => 1 + length(tl)
  }

length(x)
```

Advanced Pattern Matching

➢ Advanced Pattern Matching

```
e match {
  case P1 => e1

    …

  case Pn => en
}
```

- One can combine constructors and use _ and | in a pattern.
  (E.g) case ICons(x, INil()) | ICons(x, ICons(_, INil())) => …
- The given value e is matched against the first pattern P1.
  If succeeds, evaluate e1.
  If fails, e is matched against P2.
  If succeeds, evaluate e2.
  If fails, …
- The compiler checks exhaustiveness (ie, whether there is a missing case).

Advanced Pattern Matching: An Example

```
def secondElmt(xs: lList) : lOption =
  xs match {
    case lNil() | lCons(_,lNil()) => lNone()
    case lCons(_, lCons(x, _)) => lSome(x)
  }
```
Vs.
```
def secondElmt2(xs: lList) : lOption =
  xs match {
    case lNil() | lCons(_,lNil()) => lNone()
    case lCons(_, lCons(x, lNil())) => lSome(x)
    case _ => lNone()
  }
```
Vs.
```
def secondElmt2(xs: lList) : lOption =
  xs match {
    case lCons(_, lCons(x, lNil())) => lSome(x)
    case _ => lNone()  }
```

Pattern Matching on Int

```
def factorial(n: Int) : Int =
  n match {
    case 0 => 1
    case _ => n * factorial(n-1)
  }

def fib(n: Int) : Int =
  n match {
    case 0 | 1 => 1
    case _ => fib(n-1) + fib(n-2)
  }
```

Pattern Matching with If

```scala
def f(n: Int) : Int =
  n match {
    case 0 | 1 => 1
    case _ if (n <= 5) => 2
    case _ => 3
  }

def f(t: BTree) : Int =
  t match {
    case Leaf() => 0
    case Node(n,_,_) if (n <= 10) => 1
    case Node(_,_,_) => 2
  }
```

Exercise

Write a function "find(t: BTree, x: Int) : Boolean" that checks whether x is in t.

```scala
sealed abstract class BTree
case class Leaf() extends BTree
case class Node(value: Int, left: BTree, right: BTree)
  extends BTree
```

Solution

```scala
def find(t: BTree, i: Int) : Boolean =
  t match {
    case Leaf() => false
    case Node(n,lt,rt) =>
      if (i == n) true
      else find(lt, i) || find(rt, i)
  }

def t: BTree = Node(5,Node(4,Node(2,Leaf(),Leaf()),Leaf()),
  Node(7,Node(6,Leaf(),Leaf()),Leaf()))

find(t,7)
find(t,1)
```

Solution with Tail Recursion

```scala
def genTree(v: Int, n: Int) : BTree = {
  def genTreeIter(t: BTree, m : Int) : BTree =
    m match {
      case 0 => t
      case _ => genTreeIter(Node(v, t, Leaf()), m-1)
    }
  genTreeIter(Leaf(), n)
}
def find(t: BTree, x: Int) : Boolean = {
  def findIter(ts: BTList) : Boolean =
    ts match {
      case BTNil() => false
      case BTCons(Leaf(), tl) => findIter(tl)
      case BTCons(Node(v, l, r), tl) =>
        if (v == x) true
        else findIter(BTCons(l, BTCons(r, tl)))
    }
  findIter(BTCons(t, BTNil()))
}
find(genTree(0,10000), 1)
```

Type Checking & Inference (Concept)

What Are Types For?

➢ Typed Programming

```
def id1(x: Int): Int = x
def id2(x: Double): Double = x
```

- At run time, type information is erased (ie, `id1` = `id2`)

➢ Untyped Programming

```
def id(x) = x
```

- Do not care about types at compile time.

- But, many such languages check types at run time paying cost.

- Without run-time type check, errors can be badly propagated.

➢ What is compile-time type checking for?

- Can detect type errors at compile time.

- Increase Readability (Give a good abstraction).

- Soundness: Well-typed programs raise no type errors at run time.

Type Checking and Inference

➢ Type Checking

$$x_1:T_1, \; x_2:T_2, \; ..., \; x_n:T_n \vdash e : T$$

- `def f(x: Boolean): Boolean = x > 3`
  => Type error
- `def f(x: Int): Boolean = x > 3`

  => OK. `f: (x: Int)Boolean`

➢ Type Inference

$$x_1:T_1, \; x_2:T_2, \; ..., \; x_n:T_n \vdash e : ?$$

- `def f(x: Int) = x > 3`
  => OK by type inference. `f: (x: Int)Boolean`
- Too much type inference is not good. Why?

You can learn how type checking & inference work in
4190.310 Programming Languages

Parametric Polymorphism

Parametric Polymorphism: Functions

➢Problem

```
def id1(x: Int): Int = x
def id2(x: Double): Double = x
```

- Can we avoid copy and paste?
- Polymorphism to the rescue!

➢Parametric Polymorphism (a.k.a. For-all Types)

```
def id[A](x: A) : A = x
```

- The type of `id` is `[A](val x:A)=>A`
- `id` is a parametric expression.
- `id[T] _` is a value of type `T=>T` for any type `T`.

[We will learn other kinds of polymorphism later.]

Examples

```scala
def id[A](x:A) = x
id(3)
id("abc")

def applyn[A](f: A => A, n: Int, x: A): A =
  n match {
    case 0 => x
    case _ => f(applyn(f, n - 1, x))
  }
applyn((x:Int)=>x+1,100,3)
applyn((x:String)=>x+"!", 10, "gil")
applyn(id[String], 10, "hur")

def foo[A,B](f: A=>A, x: (A,B)) : (A,B) =
  (applyn[A](f, 10, x._1), x._2)

foo[String,Int]((x:String)=>x+"!",("abc",10))
```

Full Polymorphism using Scala's trick

```scala
type Applyn = {def apply[A](f: A=>A, n: Int, x: A): A}
object applyn {       // val applyn = new {
  def apply[A](f: A=>A, n: Int, x: A): A =
    n match {
      case 0 => x
      case _ => f(apply(f, n-1, x))
    }
}
applyn((x:String)=>x+"!", 10, "gil")
// applyn.apply[String]((x:String)=>x+"!", 10, "gil")


def foo(f: Applyn): String = {
  val a:String = f[String]((x:String)=> x + "!",10,"gil")
  val b:Int = f[Int]((x:Int)=> x + 2, 10, 5)

  a + b.toString()
}
foo(applyn)
```

Summary

➢ Main points
  • Definitions allow type parameters at the beginning.
    (E.g.) `def id[A](x: A) : A = x`

  • Values does not allow type parameters.
    (E.g.) `[A](A=>A)` is not a valid value type.

  • Record types allow type parameters in their "def" fields.
    (E.g.) `{def apply[A](x: A): A}` is a valid value type.

➢ Minor points
  • The compiler automatically inserts "`.apply`" when a record is applied to arguments.
  • The function types are encoded as "class types", which we will learn in Part II.

Parametric Polymorphism: Datatypes

```scala
sealed abstract class MyOption[A]
case class MyNone[A]() extends MyOption[A]
case class MySome[A](some: A) extends MyOption[A]


sealed abstract class MyList[A]
case class MyNil[A]() extends MyList[A]
case class MyCons[A](hd: A, tl: MyList[A]) extends MyList[A]


sealed abstract class BTree[A]
case class Leaf[A]() extends BTree[A]
case class Node[A](value: A, left: BTree[A], right: BTree[A])
extends BTree[A]

def x: MyList[Int] = MyCons(3, MyNil())
def y: MyList[String] = MyCons("abc", MyNil())
```

Exercise

```
BSTree[A] = Leaf
            | Node of Int * A * BSTree[A] * BSTree[A]
def lookup[A](t: BSTree[A], k: Int) : MyOption[A] =
  ???

def t : BSTree[String] =
  Node(5,"My5",
    Node(4,"My4",Node(2,"My2",Leaf(),Leaf()),Leaf()),
    Node(7,"My7",Node(6,"My6",Leaf(),Leaf()),Leaf()))

lookup(t, 7)
lookup(t, 3)
```

Solution

```scala
sealed abstract class BSTree[A]
case class Leaf[A]() extends BSTree[A]
case class Node[A](key: Int, value: A, left: BSTree[A], right:
BSTree[A]) extends BSTree[A]
def lookup[A](t: BSTree[A], key: Int) : MyOption[A] =
  t match {
    case Leaf() => MyNone()
    case Node(k,v,lt,rt) =>
      k match {
        case _ if key == k => MySome(v)
        case _ if key < k => lookup(lt,key)
        case _ => lookup(rt, key)
      }
  }
def t : BSTree[String] =
  Node(5,"My5",
    Node(4,"My4",Node(2,"My2",Leaf(),Leaf()),Leaf()),
    Node(7,"My7",Node(6,"My6",Leaf(),Leaf()),Leaf()))
lookup(t, 7)
lookup(t, 3)
```

A Better Way

```
sealed abstract class BTree[A]
case class Leaf[A]() extends BTree[A]
case class Node[A](value: A, left: BTree[A], right: BTree[A])
  extends BTree[A]

type BSTree[A] = BTree[(Int,A)]

def lookup[A](t: BSTree[A], k: Int) : MyOption[A] =
  ???

def t : BSTree[String] =
  Node((5,"My5"),
    Node((4,"My4"),Node((2,"My2"),Leaf(),Leaf()),Leaf()),
    Node((7,"My7"),Node((6,"My6"),Leaf(),Leaf()),Leaf()))

lookup(t, 7)
```

Solution

```scala
type BSTree[A] = BTree[(Int,A)]

def lookup[A](t: BSTree[A], key: Int) : MyOption[A] =
  t match {
    case Leaf() => MyNone()
    case Node((k,v),lt,rt) =>
      k match {
        case _ if key == k => MySome(v)
        case _ if key < k => lookup(lt,key)
        case _ => lookup(rt, key)
      }
  }

def t : BSTree[String] =
  Node((5,"My5"),
    Node((4,"My4"),Node((2,"My2"),Leaf(),Leaf()),Leaf()),
    Node((7,"My7"),Node((6,"My6"),Leaf(),Leaf()),Leaf()))

lookup(t, 7)
lookup(t, 3)
```

Polymorphic Option (Library)

➢ Option[T]

Intro:
- None
- Some(x)
- Library functions

Elim:
- Pattern matching
- Library functions

Some(3) : Option[Int]
Some("abc"): Option[String]
None: Option[Int]
None: Option[String]

Polymorphic List (Library)

➢ List[T]

Intro:

- Nil
- x :: L
- Library functions

Elim:

- Pattern matching
- Library functions

"abc"::Nil : List[String]

List(1,3,4,2,5) = 1::3::4::2::5::Nil : List[Int]

PART 2
Object-Oriented Programming

Sub Type Polymorphism (Concept)

Motivation

We want:

```
object tom {
    val name = "Tom"
    val home = "02-880-1234"
}
object bob {
    val name = "Bob"
    val mobile = "010-1111-2222"
}
def greeting(r: ???) = "Hi " + r.name + ", How are you?"
greeting(tom)
greeting(bob)
```

Note that we have

```
tom: {val name: String; val home: String}
bob: {val name: String; val mobile: String}
```

Sub Types to the Rescue!

```
type NameHome = { val name: String; val home: String }
type NameMobile = { val name: String; val mobile: String}
type Name = { val name: String }
```

NameHome <: Name   (NameHome is a sub type of Name)

NameMobile <: Name   (NameMobile is a sub type of Name)

```
def greeting(r: Name) = "Hi " + r.name + ", How are you?"
greeting(tom)
greeting(bob)
```

Sub Types

- The sub type relation is kind of the subset relation.
- But they are NOT the same.

- $T <: S$
  Every element of T can be used as that of S.

- *Cf.* T is a subset of S.
  Every element of T is that of S.

- Why polymorphism?
  A function of type S=>R can be used as T=>R for many sub types T of S.
  Note that S=>R <: T=>R when $T <: S$.

Two Kinds of Sub Types

➢Structural Sub Types
- The system implicitly determines the sub type relation by the structures of data types.
- Structurally equivalent types are treated the same.

➢Nominal Sub Types
- The user explicitly specify the sub type relation using the names of data types.
- Structurally equivalent types with different names may be treated differently.

Structural Sub Types

General Sub Type Rules

- Reflexivity:
  For any type T, we have:

$$T <: T$$

- Transitivity:
  For any types T, S, R, we have:

$$\frac{T <: R \qquad R <: S}{T <: S}$$

Sub Types for Special Types

- Nothing: The empty set
- Any: The set of all values

- For any type T, we have:

$$\text{Nothing} <: T <: \text{Any}$$

- Example
```
val a : Int = 3
val b : Any = a
def f(a: Nothing) : Int = a
```

Sub Types for Records

- Permutation

$$\frac{============================}{\{\dots; x: T1; y: T2; \dots\} <: \{\dots; \ y: T2, x: T1; \dots\}}$$

- Width

$$\frac{============================}{\{\dots; x: T; \dots\} <: \{\dots; \dots\}}$$

- Depth

$$\frac{T <: S}{\{\dots; \ x: T ; \dots\} <: \{\dots; x: S; \dots\}}$$

Sub Types for Records

- Example
  {val x: { val y: Int; val z: String}, val w: Int}
  <:   (by permutation)
  {val w: Int; val x: { val y: Int; val z: String}}
  <:   (by depth & width)
  {val w: Int; val x: {val z: String}}

Sub Types for Tuples

- Depth

$$T <: S$$

$$================================$$

$$(\ldots, T, \ldots) <: (\ldots, S, \ldots)$$

Sub Types for Functions

- Function Sub Type

$$T <: T' \qquad S <: S'$$
$$================================$$
$$(T' => S) <: (T => S')$$

- Example

```scala
def foo(s: {val a: Int; val b: Int}) :
  {val x: Int; val y: Int} = {
  object tmp {
    val x = s.b
    val y = s.a
  }
  tmp
}
val gee:
  {val a: Int; val b: Int; val c: Int} =>
  {val x: Int} =
  foo _
```

Classes

Class: Parameterized Record

```
type gee_type = {val name:String; val age: Int; def getPP(): String}
def gee_fun(_name: String, _age: Int) = {
  if (!(_age >= 0 && _age < 200)) throw new Exception("Out of range")
  new {
    val name : String = _name
    val age : Int = _age
    def getPP() : String = name + " of age " + age.toString() } }

class foo_type(_name: String, _age: Int) {
  if (!(_age >= 0 && _age < 200)) throw new Exception("Out of range")
  val name : String = _name
  val age : Int = _age
  def getPP() : String = name + " of age " + age.toString() }
val foo : foo_type = new foo_type("David Jones",25)
```

- use: foo.a foo.b foo.f
- foo is a value of foo_type
- gee is a value of gee_type

Class: No Structural Sub Typing

➢ Records: Structural sub-typing

$$foo\_type <: gee\_type$$

➢ Classes: Nominal sub-typing

$$gee\_type \not<: foo\_type$$

```
val v1 : gee_type = foo
val v2 : foo_type = gee  // type error

def greeting(r:{val name:String }) =
  "Hi " + r.name + ", How are you?"
greeting(foo)
```

Structural Types vs. Nominal Types

➢ Structural Types
- Includes arbitrary values with the required structures as elements
- Allows arbitrary types with the required structures as sub types
- Cannot assume any properties on their elements

➢ Nominal Types
- Includes only specific values as elements
- Allows only specific types as sub types
- Can assume specific properties on their elements

Class: Can be Recursive!

```scala
class MyList[A](v: A, nxt: Option[MyList[A]]) {
  val value : A = v
  val next : Option[MyList[A]] = nxt
}
type YourList[A] = Option[MyList[A]]

val t : YourList[Int] =
  Some(new MyList(3,Some (new MyList(4,None))))
```

Note on Null value

- `null`: The special element of every class & structural type

- This value is needed to construct disjoint union types using classes in Java, which, however, is not as elegant and type safe as algebraic data types (ADTs):
  - Such disjoint union types can contain junk values (not elegant).
  - Null-point exception can be raised at run time (not type safe).

- For this reason, it is discouraged to use `null` in Scala although Scala supports `null` for compatibility with Java.

- Instead, it is encouraged to use ADTs, which themselves are classes and thus take advantages of both ADT and class.

Simplification using Argument Members

```scala
class MyList[A](v: A, nxt: Option[MyList[A]]) {
  val value : A = v
  val next  : MyList[A] = nxt
}



class MyList[A](val value:A, val next:Option[MyList[A]]) {
}


class MyList[A](val value:A, val next:Option[MyList[A]])
```

Simplification using Companion Object

```scala
class MyList[A](v: A, nxt: Option[MyList[A]]) {
  val value = v
  val next = nxt
}

object MyList // val MyList = new
{ def apply[A](v: A, nxt: Option[MyList[A]]) =
    new MyList(v,nxt)
}
type YourList[A] = Option[MyList[A]]

val t0 = None
val t1 = Some(new MyList(3,Some (new MyList(4,None))))
val t2 = Some(MyList(3,Some (MyList(4,None))))
```

Exercise

Define a class "MyTree[A]" for binary trees:

MyTree[A] =
   (value: A) *
   (left: Option[MyTree[A]]) *
   (right: Option[MyTree[A]])

Solution

```scala
class MyTree[A](v: A,
               lt: Option[MyTree[A]],
               rt: Option[MyTree[A]]) {
  val value = v
  val left = lt
  val right = rt
}

type YourTree[A] = Option[MyTree[A]]

val t0 : YourTree[Int] = None
val t1 : YourTree[Int] = Some(new MyTree(3, None, None))
val t2 : YourTree[Int] =
  Some(new MyTree(3, Some (new MyTree(4,None,None)), None))
```

Nominal Sub Typing for Classes

Nominal Sub Typing, a.k.a. Inheritance

```
class foo_type(x: Int, y: Int) {
  val a : Int = x
  def b : Int = a + y
  def f(z: Int) : Int = b + y + z
}


class gee_type(x: Int) extends foo_type(x+1,x+2) {
  val c : Int = f(x) + b
}

                    gee_type <: foo_type


(new gee_type(30)).c
def test(f: foo_type) = f.a + f.b
test(new foo_type(10,20))
test(new gee_type(30))
```

Overriding 1

```
class foo_type(x: Int, y: Int) {
  val a : Int = x
  def b : Int = a + y
  def f(z: Int) : Int = b + y + z
}
class gee_type(x: Int) extends foo_type(x+1,x+2) {
  override def f(z: Int) = b + z
  // or, override def f(z: Int) = super.f(z) * 2
  val c : Int = f(x) + b
}
(new gee_type(30)).c
```

Overriding 2

```
class foo_type(x: Int, y: Int) {
  val a : Int = x
  def b : Int = a + y
  def f(z: Int) : Int = b + y + z
}


class gee_type(x: Int) extends foo_type(x+1,x+2) {
  override def b = 10
}


(new gee_type(30)).f(0)
```

Q: Can we override with a different type?

```
override def f(z: String): Int = 77    //No,  arg: diff type
def f(z: String): Int = 77             //Yes, arg: diff type
override def f(z: Int): Nothing = ??? //Yes, ret:  sub type
```

Example: My List

```scala
class MyList[A](v: A, nxt: Option[MyList[A]]) {
  val value : A = v
  val next : Option[MyList[A]] = nxt
}
type YourList[A] = Option[MyList[A]]
val t : YourList[Int] =
  Some(new MyList(3,Some (new MyList(4,None))))


class MyList[A]()
class MyNil[A]() extends MyList[A]
class MyCons[A](val hd: A, val tl: MyList[A])
  extends MyList[A]
val t: MyList[Int] =
    new MyCons(3, new MyCons(4, new MyNil()))
```

Example: MyList

```
class MyList[A]

class MyNil[A]() extends MyList[A]
object MyNil { def apply[A]() = new MyNil[A]() }

class MyCons[A](val hd: A, val tl: MyList[A])
  extends MyList[A]
object MyCons {
  def apply[A](hd:A, tl:MyList[A]) = new MyCons[A](hd, tl)}

val t: MyList[Int] = MyCons(3, MyNil())

def length(x: MyList[Int]) = ???
```

Case Class

```
class MyList[A]() { ... }
case class MyNil[A]() extends MyList[A] { ... }
object MyNil { def apply[A]() = new MyNil[A]() }
case class MyCons[A](val hd: A, val tl: MyList[A])
  extends MyList[A] { ... }
object MyCons {
  def apply[A](hd:A, tl:MyList[A]) = new MyCons[A](hd, tl)}
val t: MyList[Int] = MyCons(3, MyNil())
```

Allow Pattern Matching

```
def length(x: MyList[Int]): Int =
  x match {
    case MyNil() => 0
    case MyCons(hd, tl) => 1 + length(tl)
  }
Cf. sealed abstract class MyList[A]
```

Exercise

Define "MyTree[A]" using sub class.

```
class MyTree[A](v: A,
                lt: Option[MyTree[A]],
                rt: Option[MyTree[A]]) {
  val value = v
  val left = lt
  val right = rt
}


type YourTree[A] = Option[MyTree[A]]
```

Solution

```scala
sealed abstract class MyTree[A]
case class Empty[A]() extends MyTree[A]
case class Node[A](value: A,
                   left: MyTree[A],
                   right: MyTree[A])
  extends MyTree[A]

val t : MyTree[Int] =
  Node(3, Node(4,Empty(),Empty()), Empty())

t match {
  case Empty() => 0
  case Node(v,l,r) => v
}
```

Abstract Classes for Specification

Abstract Class: Specification

➢ Abstract Classes
  • Can be used to abstract away the implementation details.

<div align="center">

Abstract classes for Specification

Concrete sub-classes for Implementation

</div>

Abstract Class: Specification

➢Example Specification

```scala
abstract class Iter[A] {
    def getValue: Option[A]
    def getNext: Iter[A]
}


def sumElements[A](f: A=>Int)(xs: Iter[A]) : Int =
    xs.getValue match {
        case None => 0
        case Some(n) => f(n) + sumElements(f)(xs.getNext)
    }
def sumElementsId(xs:Iter[Int]) =
    sumElements((x:Int)=>x)(xs)
```

Concrete Class: Implementation

```scala
sealed abstract class MyList[A] extends Iter[A]
case class MyNil[A]() extends MyList[A] {
  def getValue = None
  def getNext = throw new Exception("...")
}
case class MyCons[A](hd: A, tl: MyList[A])
  extends MyList[A]
{
  def getValue = Some(hd)
  def getNext = tl
}


val t1 = MyCons(3, MyCons(5, MyCons(7, MyNil())))

sumElementsId(t1)
```

Exercise

Define IntCounter(n) that implements the specification Iter[A].

```
class IntCounter(n: Int) extends Iter[Int] {
  def getValue = ???
  def getNext = ???
}
```

```
sumElementsId(new IntCounter(100))
```

Solution

Define `IntCounter(n)` that implements the specification `Iter[A]`.

```scala
class IntCounter(n: Int) extends Iter[Int] {
  def getValue = if (n >= 0) Some(n) else None
  def getNext = new IntCounter(n-1)
}

sumElementsId(new IntCounter(100))
```

More on Abstract Classes

Problem: Iter for MyTree

```scala
abstract class Iter[A] {
  def getValue: Option[A]
  def getNext: Iter[A]
}

sealed abstract class MyTree[A]
case class Empty[A]() extends MyTree[A]
case class Node[A](value: A,
                   left: MyTree[A],
                   right: MyTree[A]) extends MyTree[A]
```

Q: Can MyTree[A] implement Iter[A]?
    Try it, but it is not easy.

Solution: Better Specification

```scala
abstract class Iter[A] {
  def getValue: Option[A]
  def getNext: Iter[A]
}
abstract class Iterable[A] {
  def iter : Iter[A]
}

def sumElements[A](f: A=>Int)(xs: Iter[A]) : Int =
  xs.getValue match {
    case None => 0
    case Some(n) => f(n) + sumElements(f)(xs.getNext)
  }
def sumElementsGen[A](f: A=>Int)(xs: Iterable[A]) : Int =
  sumElements(f)(xs.iter)
```

Let's Use MyList

```scala
sealed abstract class MyList[A] extends Iter[A]
case class MyNil[A]() extends MyList[A] {
  def getValue = None
  def getNext = throw new Exception("...")
}
case class MyCons[A](val hd: A, val tl: MyList[A])
  extends MyList[A] {
  def getValue = Some(hd)
  def getNext = tl
}
```

MyTree <: Iterable (Try)

```scala
sealed abstract class MyTree[A] extends Iterable[A]

case class Empty[A]() extends MyTree[A] {
  val iter = MyNil()
}

case class Node[A](value: A,
                   left: MyTree[A],
                   right: MyTree[A]) extends MyTree[A] {
  // "val iter" is more specific than "def iter",
  // so it can be used in a sub type.
  // In this example, "val iter" is also
  // more efficient than "def iter".
  val iter = MyCons(value, ???(left.iter,right.iter))
}
```

Extend MyList with append

```scala
sealed abstract class MyList[A] extends Iter[A] {
  def append(lst: MyList[A]) : MyList[A]
}
case class MyNil[A]() extends MyList[A] {
  def getValue = None
  def getNext = throw new Exception("...")
  def append(lst: MyList[A]) = lst
}
case class MyCons[A](val hd: A, val tl: MyList[A])
  extends MyList[A]
{

  def getValue = Some(hd)
  def getNext = tl
  def append(lst: MyList[A]) = MyCons(hd,tl.append(lst))
}
```

MyTree <: Iterable

```scala
sealed abstract class MyTree[A] extends Iterable[A] {
  def iter : MyList[A]
  // Note:
  // def iter : Int // Type Error because not (Int <: Iter[A])
}
case class Empty[A]() extends MyTree[A] {
  val iter = MyNil()
}
case class Node[A](value: A,
                   left: MyTree[A],
                   right: MyTree[A]) extends MyTree[A] {
  def iter = MyCons(value, left.iter.append(right.iter))
  // def iter = left.iter.append(MyCons(value,right.iter))
  // def iter = left.iter.append(right.iter.append(
  //              MyCons(value,MyNil())))
}
```

Test

```
def generateTree(n: Int) : MyTree[Int] = {
  def gen(lo:Int, hi: Int) : MyTree[Int] =
    if (lo > hi) Empty()
    else {
      val mid = (lo+hi)/2
      Node(mid, gen(lo,mid-1), gen(mid+1,hi))
    }
    gen(1,n)
}

sumElementsGen((x:Int)=>x)(generateTree(100))
```

Iter <: Iterable

```scala
abstract class Iterable[A] {
  def iter : Iter[A]
}

abstract class Iter[A] extends Iterable[A] {
  def getValue: Option[A]
  def getNext: Iter[A]
  def iter = this
}

val lst : MyList[Int] =
  MyCons(3, MyCons(4, MyCons(2,MyNil())))

sumElementsGen ((x:Int)=>x)(lst)
```

Note: tail-recursive "append"

```scala
sealed abstract class MyList[A] extends Iter[A] {
  def append(lst: MyList[A]) : MyList[A] =
    MyList.revAppend(MyList.revAppend(this, MyNil()), lst)
}
object MyList {
  // Tail-recursive functions should be written in "object"
  def revAppend[A](lst1: MyList[A], lst2: MyList[A]): MyList[A] =
    lst1 match {
      case MyNil() => lst2
      case MyCons(hd, tl) => revAppend(tl, MyCons(hd, lst2))
    }
}
case class MyNil[A]() extends MyList[A] {
  def getValue = None
  def getNext = throw new Exception("...") }
case class MyCons[A](val hd:A, val tl:MyList[A]) extends MyList[A] {
  def getValue = Some(hd)
  def getNext = tl }
```

Lazy List

Problem: Inefficiency

```scala
def time[R](block: => R): R = {
  val t0 = System.nanoTime()
  val result = block      // call-by-name
  val t1 = System.nanoTime()
  println("Elapsed time: " + ((t1 - t0)/1000000) + "ms"); result
}
def sumN[A](f: A=>Int)(n: Int, xs: Iterable[A]) : Int = {
  def sumIter(res : Int, n: Int, xs: Iter[A]) : Int =
    if (n <= 0) res
    else xs.getValue match {
      case None => res
      case Some(v) => sumIter(f(v) + res, n-1, xs.getNext)
    }
  sumIter(0,n,xs.iter)
}
// Problem: takes a few seconds to get a single value
{ val t: MyTree[Int] = generateTree(200000)
  time (sumN((x:Int) => x)(1, t)) }
```

Solution 1: Using Lists of Trees

```scala
class MyTreeIter[A](val lst: MyList[MyTree[A]]) extends Iter[A] {
  val valAndNext : (Option[A],MyList[MyTree[A]]) = lst match {
    case MyNil() => (None, MyNil())
    case MyCons(hd,tl) => hd match {
      case Empty() => throw new Exception("...")
      case Node(v,Empty(),Empty()) => (Some(v), tl)
      case Node(v,lt,Empty()) => (Some(v), MyCons(lt,tl))
      case Node(v,Empty(),rt) => (Some(v), MyCons(rt,tl))
      case Node(v,lt,rt) => (Some(v), MyCons(lt,MyCons(rt,tl)))
    }
  }
  val getValue = valAndNext._1
  def getNext = new MyTreeIter(valAndNext._2)
}
```

Lazy Iteration using Lists of Trees

```
sealed abstract class MyTree[A] extends Iterable[A]
case class Empty[A]() extends MyTree[A] {
  val iter = new MyTreeIter(MyNil())
}
case class Node[A](value: A,
                   left: MyTree[A],
                   right: MyTree[A]) extends MyTree[A]
{
  val iter = new MyTreeIter(MyCons(this,MyNil()))
}

{ val t: MyTree[Int] = generateTree(200000)
  time (sumN((x:Int) => x)(100, t))
  time (sumN((x:Int) => x)(100000, t))
}
```

Solution 2: Lazy List

```scala
abstract class LazyList[A] extends Iter[A] {
  def head : Option[A]
  def tail : LazyList[A]
  def append(lst: LazyList[A]) : LazyList[A]
  def getValue = head
  def getNext = tail
}
case class LNil[A]() extends LazyList[A] {
  val head = None
  val tail = this
  def append(lst: LazyList[A]) = lst
}
class LCons[A](ht: =>(A, LazyList[A])) extends LazyList[A] {
  lazy val (hd,tl) = ht
  def head = Some(hd)
  def tail = tl
  def append(lst: LazyList[A]) = LCons(hd, tl.append(lst)) }
object LCons{ def apply[A](ht: =>(A,LazyList[A])) = new LCons(ht) }
```

Note: "append" is not recursive!!!

Lazy Iteration using LazyList

```scala
sealed abstract class MyTree[A] extends Iterable[A] {
  def iter : LazyList[A]
}
case class Empty[A]() extends MyTree[A] {
  val iter = LNil()
}
```

Note: "iter" is not recursive!!!

```scala
case class Node[A](value: A,
                   left: MyTree[A],
                   right: MyTree[A]) extends MyTree[A] {
  lazy val iter = LCons(value, left.iter.append(right.iter))
  // lazy val iter = left.iter.append(LCons(value,right.iter))
  // lazy val iter = left.iter.append(right.iter.append(
  //                    LCons(value,LNil())))
}
{ val t: MyTree[Int] = generateTree(200000)
  time (sumN((x:Int) => x)(100, t))
  time (sumN((x:Int) => x)(100000, t))
}
```

Wrapper for Inheritance

Using a Wrapper Class

```scala
abstract class Iter[A] {
  def getValue: Option[A]
  def getNext: Iter[A]
}

class ListIter[A](val list: List[A]) extends Iter[A] {
  def getValue = list.headOption
  def getNext = new ListIter(list.tail)
}

sumElements((x:Int)=>x)(new ListIter(List(1,2,3,4)))
```

MyTree Using ListIter

```scala
abstract class Iterable[A] {
  def iter : Iter[A]
}
sealed abstract class MyTree[A] extends Iterable[A] {
  override def iter : ListIter[A]
}
case class Empty[A]() extends MyTree[A] {
  val iter : ListIter[A] = new ListIter(Nil)
}
case class Node[A](value: A,
                   left: MyTree[A],
                   right: MyTree[A])
  extends MyTree[A] {
  val iter : ListIter[A] = new ListIter(
    value::(left.iter.list ++ right.iter.list))
}
```

Test

```
val t : MyTree[Int] =
  Node(3, Node(4,Node(2,Empty(),Empty()),
    Node(3,Empty(),Empty())),
    Node(5,Empty(),Empty()))

sumElementsGen((x:Int)=>x)(t)
```

Abstract Class With Abstract Types

Using an Abstract Type

```scala
abstract class Iterable[A] {
  type iter_t
  def iter: iter_t
  def getValue(i: iter_t) : Option[A]
  def getNext(i: iter_t) : iter_t
}

def sumElements[A](f:A=>Int)(xs: Iterable[A]) : Int = {
  def sumElementsIter(i: xs.iter_t) : Int =
    xs.getValue(i) match {
      case None => 0
      case Some(n) => f(n) + sumElementsIter(xs.getNext(i))
    }
  sumElementsIter(xs.iter)
}
```

MyTree Using List

```scala
sealed abstract class MyTree[A] extends Iterable[A] {
  type iter_t = List[A]
  def getValue(i: List[A]): Option[A] = i.headOption
  def getNext(i: List[A]): List[A] = i.tail
}
case class Empty[A]() extends MyTree[A] {
  val iter : List[A] = Nil
}
case class Node[A](value: A,
                   left: MyTree[A], right: MyTree[A])
  extends MyTree[A] {
  val iter = value :: (left.iter ++ right.iter) //Pre-order
//val iter = left.iter ++ (value :: right.iter) // In-order
//val iter = left.iter ++ (right.iter ++ List(value))
                                              //Post-order
}
```

Test

```
val t : MyTree[Int] =
  Node(3, Node(4,Node(2,Empty(),Empty()),
    Node(3,Empty(),Empty())),
    Node(5,Empty(),Empty()))

sumElements((x:Int)=>x)(t)
```

Abstract Class with Arguments

Abstract Class with Arguments

```scala
abstract class IterableHE[A](eq: (A,A) => Boolean)
  extends Iterable[A]
{

  def hasElement(a: A) : Boolean = {
    def hasElementIter(i: iter_t) : Boolean =
      getValue(i) match {
        case None => false
        case Some(n) =>
          if (eq(a,n)) true
          else hasElementIter(getNext(i))
      }
    hasElementIter(iter)
  }
}
```

MyTree

```scala
sealed abstract class MyTree[A](eq:(A,A)=>Boolean)
  extends IterableHE[A](eq) {
  type iter_t = List[A]
  def getValue(i : List[A]) : Option[A] = i.headOption
  def getNext(i: List[A]) : List[A] = i.tail
}

case class Empty[A](eq: (A,A)=>Boolean)
  extends MyTree[A](eq) {
  val iter : List[A] = Nil
}

case class Node[A](eq: (A,A)=>Boolean,
                value: A, left: MyTree[A], right: MyTree[A])
  extends MyTree[A](eq) {
  val iter : List[A] = value :: (left.iter ++ right.iter)
}
```

Test

```scala
val leq = (x:Int,y:Int) => x == y
val lEmpty = Empty(leq)
def lNode(n: Int, t1: MyTree[Int], t2: MyTree[Int]) =
  Node(leq,n,t1,t2)

val t : MyTree[Int] =
  lNode(3, lNode(4,lNode(2,lEmpty,lEmpty),
                    lNode(3,lEmpty,lEmpty)),
           lNode(5,lEmpty,lEmpty))

sumElements((x:Int)=>x)(t)
t.hasElement(5)
t.hasElement(10)
```

Alternatively, Argument Elimination

```scala
abstract class IterableHE[A]
  extends Iterable[A]
{

  def eq(a:A, b:A) : Boolean
  def hasElement(a: A) : Boolean = {
    def hasElementIter(i: iter_t) : Boolean =
      getValue(i) match {
        case None => false
        case Some(n) =>
          if (eq(a,n)) true
          else hasElementIter(getNext(i))
      }
    hasElementIter(iter)
  }
}
```

MyTree

```scala
sealed abstract class MyTree[A] extends IterableHE[A] {
  type iter_t = List[A]
  def getValue(i : List[A]) : Option[A] = i.headOption
  def getNext(i: List[A]) : List[A] = i.tail
}
case class Empty[A](_eq:(A,A)=>Boolean) extends MyTree[A] {
  def eq(a:A, b:A) = _eq(a,b)
  val iter : List[A] = Nil
}

case class Node[A](_eq: (A,A)=>Boolean,
                value: A, left: MyTree[A], right: MyTree[A])
  extends MyTree[A] {
  def eq(a:A, b:A) = _eq(a,b)
  val iter : List[A] = value :: (left.iter ++ right.iter)
}
```

Test

```
val leq = (x:Int,y:Int) => x == y
val lEmpty = Empty(leq)
def lNode(n: Int, t1: MyTree[Int], t2: MyTree[Int]) =
  Node(leq,n,t1,t2)

val t : MyTree[Int] =
  lNode(3, lNode(4,lNode(2,lEmpty,lEmpty),
                    lNode(3,lEmpty,lEmpty)),
           lNode(5,lEmpty,lEmpty))

sumElements((x:Int)=>x)(t)
t.hasElement(5)
t.hasElement(10)
```

More on Classes

Motivating Example

```scala
class Primes(val prime: Int, val primes: List[Int]) {
  def getNext: Primes = {
    val p = computeNextPrime(prime + 2)
    new Primes(p, primes ++ (p :: Nil))
  }
  def computeNextPrime(n: Int) : Int =
    if (primes.forall((p:Int) => n%p != 0)) n
    else computeNextPrime(n+2)
}

def nthPrime(n: Int): Int = {
  def go(primes: Primes, k: Int): Int =
    if (k <= 1) primes.prime
    else go(primes.getNext, k - 1)
  if (n == 0) 2 else go(new Primes(3, List(3)), n)
}
nthPrime(10000)
```

Multiple Constructors

```scala
class Primes(val prime: Int, val primes: List[Int]) {
  def this() = this(3, List(3))
  def getNext: Primes = {
    val p = computeNextPrime(prime + 2)
    new Primes(p, primes ++ (p :: Nil))
  }
  def computeNextPrime(n: Int) : Int =
    if (primes.forall((p:Int) => n%p != 0)) n
    else computeNextPrime(n+2)
}

def nthPrime(n: Int): Int = {
  def go(primes: Primes, k: Int): Int =
    if (k <= 1) primes.prime
    else go(primes.getNext, k - 1)
  if (n == 0) 2 else go(new Primes, n)
}
nthPrime(10000)
```

Access Modifiers

➢ Access Modifiers
  - Private: Only the class can access the member.
  - Protected: Only the class and its sub classes can access the member.

Using Access Modifiers

```scala
class Primes private (val prime:Int, protected val primes:List[Int])
{ def this() = this(3, List(3))
  def getNext: Primes = {
    val p = computeNextPrime(prime + 2)
    new Primes(p, primes ++ (p :: Nil))
  }
  private def computeNextPrime(n: Int) : Int =
    if (primes.forall((p:Int) => n%p != 0)) n
    else computeNextPrime(n+2)
}

def nthPrime(n: Int): Int = {
  def go(primes: Primes, k: Int): Int =
    if (k <= 1) primes.prime
    else go(primes.getNext, k - 1)
  if (n == 0) 2 else go(new Primes, n)
}
nthPrime(10000)
```

Using Specification

➢ OOP-style Specification

```
abstract class PrimesSig {
  // Problem: need an instance of PrimesSig to make a new instance
  def makeNew : PrimesSig
  def prime : Int
  def getNext : PrimesSig
}
```

➢ Type class-style Specification

```
abstract class PrimesSig[P] {
  def makeNew : P
  def prime(p: P) : Int
  def getNext(p: P) : P
}
def nthPrime[P](tc: PrimesSig[P])(n: Int): Int = {
  def go(p: P, k: Int): Int =
    if (k <= 1) tc.prime(p) else go(tc.getNext(p), k - 1)
  if (n == 0) 2 else go(tc.makeNew, n)
}
```

Implementation

```scala
class Primes private (val prime:Int, protected val primes:List[Int])
{ def this() = this(3, List(3))
  def getNext: Primes = {
    val p = computeNextPrime(prime + 2)
    new Primes(p, primes ++ (p :: Nil))
  }
  private def computeNextPrime(n: Int) : Int =
    if (primes.forall((p:Int) => n%p != 0)) n
    else computeNextPrime(n+2)
}
class PrimesImpl extends PrimesSig[Primes] {
  def makeNew = new Primes
  def prime(p: Primes) = p.prime
  def getNext(p: Primes) = p.getNext
}
val primesTC = new PrimesImpl

nthPrime(primesTC)(10000)
```

Traits for Multiple Inheritance

Multiple Inheritance Problem

➢ Multiple Inheritance
  • The famous "diamond problem"

```
class A(val a: Int)
class B extends A(10)
class C extends A(20)
class D extends B, C.
```

Problem 1: What is the value of (new D).a ?

Problem 2: The constructor of A must be executed once
           because A may contain side effects such as
           sending messages over the network.

Java's Solution: Interface

➢Interface
- An interface cannot contain any implementation but only types of its methods.
- A class can inherit implementations from only one parent class but implement multiple interfaces.

Scala's Solution: Trait

- ➢ Traits
  - A trait can implement any of its methods,
    but should have only one constructor with no arguments.
  - A trait X can
    "extend" only one trait or (abstract) class with no arguments
    "with" multiple traits $T_1 , \ldots , T_n$
    s.t. the superclass of X is a subclass of the superclass of T_i for all i
  - An (abstract) class X can
    "extend" only one trait or (abstract) class with any arguments
    "with" multiple traits $T_1 , \ldots , T_n$
    s.t. the superclass of X is a subclass of the superclass of T_i for all i
  - No cyclic inheritance is allowed.
- ➢ Property
  - Among the ancestors of a class, for the same class:
    - A constructor with arguments can appear at most once
    - A constructor with no argument can appear multiple times

Example

```scala
class A(val a : Int) {
  def this () = this(0)
}
trait B {
  def f(x: Int): Int = x
}
trait C extends A with B {
  def g(x: Int): Int = x + a
}
trait D extends B {
  def h(x: Int): Int = f(x + 50)
}
class E extends A(10) with C with D {
  override def f(x: Int) = x * a
}

val e = new E
```

Algorithm for Multiple Inheritance

➢ Algorithm
- Give a linear order among all ancestors by "post-order" traversing without revisiting the same node.
- Invoke the constructors once in that order.

  Note. Post-order traversal of a class C means
  - Recursively post-order traverse C's first parent; …;
  - Recursively post-order traverse C's last parent; and
  - Visit C.

  By post-order traversing from "E" in the previous example,
  we have the order: `A(10) -> B -> C -> D -> E`

  ```
  val e = new E
  e.a // 10                    e.f(100) // 100*10
  e.g(100) // 100 + 10         e.h(100) // (100 + 50) * 10
  ```

- A constructor with arguments is always visited before the same constructor with no arguments.
- Compile error if the same field is implemented by multiple classes

A Simple Example With Traits

Motivation

```scala
abstract class Iter[A] {
  def getValue: Option[A]
  def getNext: Iter[A]
}


class ListIter[A](val list: List[A]) extends Iter[A] {
  def getValue = list.headOption
  def getNext = new ListIter(list.tail)
}


abstract class Dict[K,V] {
  def add(k: K, v: V): Dict[K,V]
  def find(k: K): Option[V]
}
```

Q: How can we extend ListIter and implement Dict?

Specification using Traits

```
// abstract class Dict[K,V] {
//    def add(k: K, v: V): Dict[K,V]
//    def find(k: K): Option[V] }

trait Dict[K,V] {
  def add(k: K, v: V): Dict[K,V]
  def find(k: K): Option[V]
}
```

Implementing Traits

```scala
class ListIterDict[K,V]
       (eq: (K,K)=>Boolean, list: List[(K,V)])
      extends ListIter[(K,V)](list)
         with Dict[K,V]
{
  def add(k:K,v:V) = new ListIterDict(eq,(k,v)::list)
  def find(k: K) : Option[V] = {
    def go(l: List[(K, V)]): Option[V] = l match {
        case Nil => None
        case (k1, v1) :: tl =>
          if (eq(k, k1)) Some(v1) else go(tl) }
    go(list) }
}
```

Test

```scala
def sumElements[A](f: A=>Int)(xs: Iter[A]) : Int =
  xs.getValue match {
    case None => 0
    case Some(n) => f(n) + sumElements(f)(xs.getNext)
  }

def find3(d: Dict[Int,String]) = {
  d.find(3)
}

val d0 = new ListIterDict[Int,String]((x,y)=>x==y,Nil)
val d = d0.add(4,"four").add(3,"three")

sumElements[(Int,String)](x=>x._1)(d)
find3(d)
```

Without Using Inheritance

```
class ListIterDict[K,V]
    (eq: (K,K)=>Boolean, list: List[(K,V)])
    extends Iter[(K,V)] with Dict[K,V]
{

  val listIter = new ListIter(list)
  def getValue = listIter.getValue
  def getNext = listIter.getNext

  def add(k:K,v:V) = new ListIterDict(eq,(k,v)::list)
  def find(k: K) : Option[V] = {
    def go(l: List[(K, V)]): Option[V] = l match {
      case Nil => None
      case (k1, v1) :: tl =>
        if (eq(k, k1)) Some(v1) else go(tl) }
    go(list) }
}
```

Mixin with Traits

Motivation: Mixin Functionality

```scala
abstract class Iter[A] {
  def getValue: Option[A]
  def getNext: Iter[A]
}


class ListIter[A](list: List[A]) extends Iter[A]
{

  def getValue = list.headOption
  def getNext: Iter[A] = new ListIter(list.tail)
}


trait MRIter[A] extends Iter[A] {
  def mapReduce[B,C](combine: (B,C)=>C, ival: C, f: A=>B): C = ???
}
```

Mixin Composition

```scala
trait MRIter[A] extends Iter[A] {
  override def getNext: MRIter[A]
  def mapReduce[B,C](combine: (B,C)=>C, ival: C, f: A=>B): C =
    getValue match {
      case None => ival
      case Some(v) =>
        combine(f(v), getNext.mapReduce(combine, ival, f))
    }
}


class MRListIter[A](list: List[A])
  extends ListIter (list) with MRIter[A]
{
  override def getNext: MRIter[A] = new MRListIter(list.tail)
}


val mr = new MRListIter[Int](List(3,4,5))
mr.mapReduce[Int,Int]((b,c)=>b+c,0,(a)=>a*a)
```

Mixin Composition: A Better Way

```scala
trait MRIter[A] extends Iter[A] {
  def mapReduce[B,C](combine: (B,C)=>C, ival: C, f: A=>B): C = {
    def go(c: Iter[A]): C = c.getValue match {
      case None => ival
      case Some(v) => combine(f(v), go(c.getNext))
    }
    go(this)
  }
}

class MRListIter[A](list: List[A])
  extends ListIter (list) with MRIter[A]

val mr = new MRListIter[Int](List(3,4,5))

// or, val mr = new ListIter(List(3,4,5)) with MRIter[Int]

mr.mapReduce[Int,Int]((b,c)=>b+c,0,(a)=>a*a)
```

Syntactic Sugar: new A with B with C { ... }

```
new A with B1 ⋯ with Bm {
   code
}
```

is equivalent to

```
{
   class _tmp_ extends A with B1 ⋯ with Bm {
      code
   }
   new _tmp_
}
```

Stacking with Traits

Typical Hierarchy in Scala
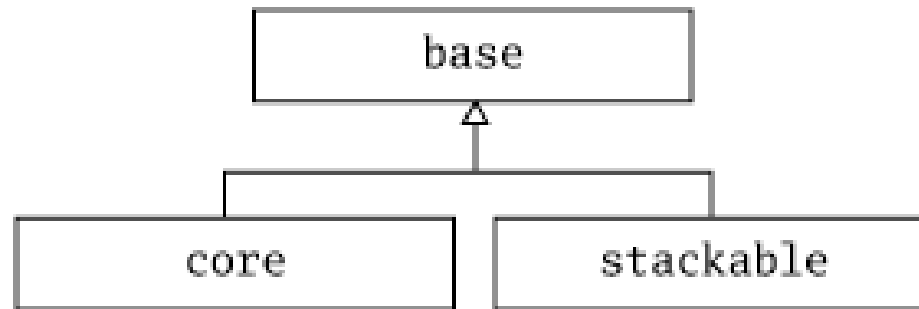
- **BASE**
  Interface (trait or abstract class)

- **CORE**
  Functionality (trait or concrete class)

- **CUSTOM**
  Modifications (each in a separate, composable trait)

IntStack: Base

> **BASE**

```
trait Stack[A] {
  def get(): (A,Stack[A])
  def put(x: Int): Stack[A]
}
```

IntStack: Core

➤**CORE**

```scala
class BasicIntStack protected (xs: List[Int]) extends Stack[Int]
{
  override val toString = "Stack:" + xs.toString
  def this() = this(Nil)
  protected def mkStack(xs: List[Int]): Stack[Int] =
    new BasicIntStack(xs)
  def get(): (Int,Stack[Int]) = (xs.head, mkStack(xs.tail))
  def put(x: Int): Stack[Int] = mkStack(x :: xs)
}

val s0 = new BasicIntStack
val s1 = s0.put(3)
val s2 = s1.put(-2)
val s3 = s2.put(4)
val (v1,s4) = s3.get()
val (v2,s5) = s4.get()
```

IntStack: Custom Modifications

➢**CUSOM**

```scala
trait Doubling extends Stack[Int] {
  abstract override def put(x: Int): Stack[Int] = super.put(2 * x)
}


trait Incrementing extends Stack[Int] {
  abstract override def put(x: Int): Stack[Int] = super.put(x + 1)
}


trait Filtering extends Stack[Int] {
  abstract override def put(x: Int): Stack[Int] =
    if (x >= 0) super.put(x) else this
}
```

IntStack: Stacking

➢**Stacking**

```scala
class DIFIntStack protected (xs: List[Int])
  extends BasicIntStack(xs)
  with Doubling with Incrementing with Filtering
{
  def this() = this(Nil)
  override def mkStack(xs: List[Int]): Stack[Int] =
    new DIFIntStack(xs)
}

val s0 = new DIFIntStack
val s1 = s0.put(3)
val s2 = s1.put(-2)
val s3 = s2.put(4)
val (v1,s4) = s3.get()
val (v2,s5) = s4.get()
```

Intersection Types

Intersection Types

➢ Typing Rule

$$\frac{t : T1 \qquad t : T2}{t : T1 \text{ with } T2}$$

➢ Example

```scala
trait A { val a: Int = 0 }
trait B { val b: Int = 0 }
class C extends A with B {
  override val a = 10
  override val b = 20
  val c = 30
}

val x = new C
val y: A with B = x
y.a // 10
y.b // 20
y.c // type error
```

Subtype Relation for "with"

The subtype relation for "with" is structural.

- Permutation

$$\frac{\rule{0pt}{0pt}\hspace{6cm}}{\ldots \text{ with } T1 \text{ with } T2 \ldots <: \ldots \text{ with } T2 \text{ with } T1 \ldots}$$

- Width

$$\frac{\rule{0pt}{0pt}\hspace{5cm}}{\ldots \text{ with } T \ldots <: \ldots \ldots}$$

- Depth

$$\frac{T <: S}{\ldots \text{ with } T \ldots <: \ldots \text{ with } S \ldots}$$

Additional Resources

➤ Traits
- http://www.scala-lang.org/old/node/126

➤ Mixin Composition
- http://www.scala-lang.org/old/node/117

➤ Stackable Trait Pattern
- http://www.artima.com/scalazine/articles/stackable_trait_pattern.html

➤ Multiple Inheritance via Traits
- https://www.safaribooksonline.com/blog/2013/05/30/traits-how-scala-tames-multiple-inheritance/

➤ UCSD CSE 130
- http://cseweb.ucsd.edu/classes/wi14/cse130-a/lectures/scala/02-classes.html

PART 3
Type Classes for Specifications

Specifications over Parameter Types

Subtype Polymorphism

```scala
trait Ord {
  // this cmp that < 0  iff this < that
  // this cmp that > 0  iff this > that
  // this cmp that == 0 iff this == that
  def cmp(that: Ord): Int

  def ===(that: Ord): Boolean = (this.cmp(that)) == 0
  def <  (that: Ord): Boolean = (this cmp that) < 0
  def >  (that: Ord): Boolean = (this cmp that) > 0
  def <= (that: Ord): Boolean = (this cmp that) <= 0
  def >= (that: Ord): Boolean = (this cmp that) >= 0
}
def max3(a: Ord, b: Ord, c: Ord) : Ord =
  if (a <= b) { if (b <= c) c else b }
  else        { if (a <= c) c else a }
```

* Problem: hard (almost impossible) to implement Ord (e.g., using Int)

Specification over Parameter Types

```scala
trait Ord[A] {
  def cmp(that: Ord[A]): Int
  def getValue : A

  def ===(that: Ord[A]): Boolean = (this.cmp(that)) == 0
  def <  (that: Ord[A]): Boolean = (this cmp that) < 0
  def >  (that: Ord[A]): Boolean = (this cmp that) > 0
  def <= (that: Ord[A]): Boolean = (this cmp that) <= 0
  def >= (that: Ord[A]): Boolean = (this cmp that) >= 0
}
def max3[A](a: Ord[A], b: Ord[A], c: Ord[A]) : Ord[A] =
  if (a <= b) {if (b <= c) c else b }
  else        {if (a <= c) c else a }

class OInt(val getValue : Int) extends Ord[Int] {
  def cmp(that: Ord[Int]) = getValue - that.getValue
}
max3(new OInt(3), new OInt(2), new OInt(10)).getValue
```

Further example: Ordered Bag

```scala
class Bag[U] protected (val toList: List[Ord[U]]) {
  def this() = this(Nil)
  def add(x: Ord[U]) : Bag[U] = {
    def go(elmts: List[Ord[U]]): List[Ord[U]] =
      elmts match {
        case Nil => x :: Nil
        case e :: _ if (x < e) => x :: elmts
        case e :: _ if (x === e) => elmts
        case e :: rest => e :: go(rest)
      }
    new Bag(go(toList))
  }
}
val emp = new Bag[Int]()
val b = emp.add(new OInt(3)).add(new OInt(2)).
          add(new OInt(10)).add(new OInt(2))
b.toList.map((x)=>x.getValue)
```

Problem: each data carries operations

```scala
class OInt2(val getValue : Int) extends Ord[Int] {
  def cmp(that: Ord[Int]) = that.getValue - getValue
}

val c = emp.add(new OInt(3)).add(new OInt2(2)).
          add(new OInt(10)).add(new OInt(2))
c.toList.map((x)=>x.getValue)
```

Type Classes

Completely Separating Ord from Int

```scala
abstract class Ord[A] {
  def cmp(me: A, you: A): Int

  def ===(me: A, you: A): Boolean = cmp(me,you) == 0
  def <  (me: A, you: A): Boolean = cmp(me,you) < 0
  def >  (me: A, you: A): Boolean = cmp(me,you) > 0
  def <= (me: A, you: A): Boolean = cmp(me,you) <= 0
  def >= (me: A, you: A): Boolean = cmp(me,you) >= 0
}

def max3[A](a: A, b: A, c: A)(implicit ord: Ord[A]) : A =
  if (ord.<=(a, b)) {if (ord.<=(b,c)) c else b }
  else               {if (ord.<=(a,c)) c else a }

implicit val intOrd : Ord[Int] = new Ord[Int] {
  def cmp(me: Int, you: Int) = me - you }

max3(3,2,10) // 10
```

Implicit

➢Implicit
- An argument is given "implicitly"

```scala
def foo(s: String)(implicit t: String) = s + t

implicit val exclamation : String = "!!!!!!"

foo("Hi")
foo("Hi")("???") // can give it explicitly
```

Bag Example

```scala
class Bag[A] protected (val toList: List[A])(implicit ord: Ord[A])
{ def this()(implicit ord: Ord[A]) = this(Nil)(ord)

  def add(x: A) : Bag[A] = {
    def go(elmts: List[A]) : List[A] =
      elmts match {
        case Nil => x :: Nil
        case e :: _ if (ord.<(x,e)) => x :: elmts
        case e :: _ if (ord.===(x,e)) => elmts
        case e :: rest => e :: go(rest)
      }
    new Bag(go(toList))
  }
}

(new Bag[Int]()).add(3).add(2).add(3).add(10).toList
```

Implicitly

➢Definition

```
def implicitly[A](implicit a: A) : A = a
```

➢Example

```
class Bag[A] protected (val toList: List[A])(implicit ord: Ord[A])
{ def this()(implicit ord: Ord[A]) = this(Nil)(ord)
  ...

        case e :: _ if (ord.===(x,e)) => elmts
  ...
}
```

is equivalent to

```
class Bag[A : Ord] protected (val toList: List[A])
{ def this() = this(Nil)
  ...

        case e :: _ if (implicitly[Ord[A]].===(x,e)) => elmts
  ...

}
```

Bag Example Implicitly

```scala
class Bag[A : Ord] protected (val toList: List[A])
{ def this() = this(Nil)

  def add(x: A) : Bag[A] = {
    def go(elmts: List[A]) : List[A] =
      elmts match {
        case Nil => x :: Nil
        case e :: _ if (implicitly[Ord[A]].<(x,e)) => x :: elmts
        case e :: _ if (implicitly[Ord[A]].===(x,e)) => elmts
        case e :: rest => e :: go(rest)
      }
    new Bag(go(toList))
  }
}

(new Bag[Int]()).add(3).add(2).add(3).add(10).toList
```

Bootstrapping Implicits

```scala
// lexicographic order
implicit def tupOrd[A, B](implicit ordA: Ord[A], ordB: Ord[B])
  : Ord[(A, B)] =
  new Ord[(A, B)] {
    def cmp(me: (A, B), you: (A, B)) : Int = {
      val c1 = ordA.cmp(me._1, you._1)
      if (c1 != 0) c1
      else { ordB.cmp(me._2, you._2) }
    }
  }


val b = new Bag[(Int,(Int,Int))]
b.add((3,(3,4))).add((3,(2,7))).add((4,(0,0))).toList
```

With Different Orders

```scala
val intOrdRev : Ord[Int] =
  new Ord[Int] { def cmp(me: Int, you: Int) = you - me }

(new Bag[Int]()(intOrdRev)).add(3).add(2).add(10).toList
```

Type Classes With Multiple Parameters

Interfaces I

```scala
// trait Iter[A] {
//   def getValue: Option[A]
//   def getNext: Iter[A]
// }
trait Iter[I,A] {
  def getValue(i: I): Option[A]
  def getNext(i: I): I
}


// trait Iterable[A] {
//   def iter : Iter[A]
// }
trait Iterable[R,I,A] {
  def iter(a: R): I
  def iterIF: Iter[I, A]
}
```

Interfaces II

```scala
trait ListIF[L,A] {
  def empty : L
  def head(l: L) : Option[A]
  def tail(l: L) : L
  def cons(a: A, l: L) : L
  def append(l1: L, l2: L) : L
}

trait TreeIF[T,A] {
  def empty : T
  def node(a: A, l: T, r: T) : T
  def head(t: T) : Option[A]
  def left(t: T) : T
  def right(t: T) : T
}
```

Programs for Testing: use Iter, Iterable

```scala
def sumElements[I](xs: I)(implicit IT: Iter[I,Int]) : Int =
  IT.getValue(xs) match {
    case None => 0
    case Some(n) => n + sumElements(IT.getNext(xs)) }

def printElements[I,A](xs: I)(implicit IT: Iter[I,A]) : Unit =
  IT.getValue(xs) match {
    case None =>
    case Some(n) => {printIn(n); printElements(IT.getNext(xs))}}

def sumElements2[R,I](xs: R)(implicit ITR: Iterable[R,I,Int]) =
  sumElements(ITR.iter(xs))(ITR.iterIF)
//sumElements[I](ITR.iter(xs))(ITR.iterIF)

def printElements2[R,I,A](xs: R)(implicit ITR: Iterable[R,I,A]) =
  printElements(ITR.iter(xs))(ITR.iterIF)
//printElements[I,A](ITR.iter(xs))(ITR.iterIF)
```

Programs for Testing: use All

```
def testList[L](implicit LI: ListIF[L,Int], IT: Iter[L,Int]) {
  val l = LI.cons(3, LI.cons(5, LI.cons(2, LI.cons(1, LI.empty))))
  println(sumElements(l)) //sumElements(l)(listIter[Int])
  printElements(l) //printElements(l)(listIter[Int])
}

def testTree[T,L](implicit TI: TreeIF[T,Int],
                           ITR: Iterable[T,L,Int]) {
  val t: T = TI.node(3, TI.node(4, TI.empty, TI.empty),
                        TI.node(2, TI.empty, TI.empty))
  println(sumElements2(t))
  printElements2(t)
}
```

List: provide Iter, ListIF

```scala
implicit def listIter[A] : Iter[List[A], A] =
  new Iter[List[A],A] {
    def getValue(a: List[A]) = a.headOption
    def getNext(a: List[A]) = a.tail
  }


implicit def listIF[A] : ListIF[List[A],A] =
  new ListIF[List[A],A] {
    def empty: List[A] = Nil
    def head(l: List[A]) = l.headOption
    def tail(l: List[A]) = l.tail
    def cons(a: A, l: List[A]) = a :: l
    def append(l1: List[A], l2: List[A]) = l1 ::: l2
  }
```

MyTree: use Iter, ListIF, provide Iterable, TreeIF

```scala
sealed abstract class MyTree[A]
case class Empty[A]() extends MyTree[A]
case class Node[A](value: A, left: MyTree[A], right: MyTree[A])
  extends MyTree[A]


implicit def treeIterable[L,A]
  (implicit IF: ListIF[L,A], IT: Iter[L,A]) =
  new Iterable[MyTree[A], L, A] {
    def iter(a: MyTree[A]): L = a match {
      case Empty() => IF.empty
      case Node(v, left, right) =>
        IF.cons (v, IF.append(iter(left), iter(right)))    }
    val iterIF = IT }
```

MyTree: use Iter, ListIF, provide Iterable, TreeIF

```scala
implicit def treeIF[A] : TreeIF[MyTree[A],A] =
  new TreeIF[MyTree[A],A] {
    def empty = Empty()
    def node(a: A, l: MyTree[A], r: MyTree[A]) = Node(a,l,r)
    def head(t: MyTree[A]) = t match {
      case Empty() => None
      case Node(v,_,_) => Some(v)      }
    def left(t: MyTree[A]) = t match {
      case Empty() => t
      case Node(_,lt,_) => lt      }
    def right(t: MyTree[A]) = t match {
      case Empty() => t
      case Node(_,_,rt) => rt      }
  }
```

Linking Modules

```
testList[List[Int]]

testTree[MyTree[Int],List[Int]]
```

Refined Interfaces

```scala
trait ListProdIF[L,A] {
  def empty : L
  def cons(a: A, l: L) : L
  def append(l1: L, l2: L) : L
}

implicit def treeIterable[L,A]
  (implicit IF: ListProdIF[L,A], IT: Iter[L,A]) =
  new Iterable[MyTree[A], L, A] {
    def iter(a: MyTree[A]): L = a match {
      case Empty() => IF.empty
      case Node(v, left, right) =>
        IF.cons (v, IF.append(iter(left), iter(right)))    }
    val iterIF = IT }
```

Linking Modules

```
implicit def List2ListProdIF[L,A]
    (implicit IF: ListIF[L,A]) : ListProdIF[L,A] =
  new ListProdIF[L,A] {
    def empty = IF.empty
    def cons(a: A, l: L) = IF.cons(a,l)
    def append(l1: L, l2: L) = IF.append(l1, l2)
  }


testList[List[Int]]

testTree[MyTree[Int],List[Int]]
```

Iter being Iterable

```scala
implicit def iterIterable[I,A](implicit IT: Iter[I,A]) =
  new Iterable[I,I,A] {
    def iter(a: I) = a
    val iterIF = IT
  }

val l = List(3,5,2,1)
sumElements2(l) //sumElements2(iterIterable(listIter[Int]))
printElements2(l) //printElements2(iterIterable(listIter[Int]))
```

Higher-kind Type Classes

Interfaces I

```scala
import scala.language.higherKinds

//trait Iter[I,A] {
//  def getValue(a: I): Option[A]
//  del getNext(a: I): I }
abstract class Iter[I[_]] {
  def getValue[A](a: I[A]) : Option[A]
  def getNext[A](a: I[A]) : I[A]
}
//trait Iterable[R,I,A] {
//  def iter(a: R): I
//  def iterIF: Iter[I, A]
//}
abstract class Iterable[R[_]] {
  type I[_]
  def iter[A](a: R[A]): I[A]
  def iterIF: Iter[I]
}
```

Interfaces II

```scala
trait ListIF[L[_]] {
  def empty[A] : L[A]
  def head[A](l: L[A]) : Option[A]
  def tail[A](l: L[A]) : L[A]
  def cons[A](a: A, l: L[A]) : L[A]
  def append[A](l1: L[A], l2: L[A]) : L[A]
}

trait TreeIF[T[_]] {
  def empty[A] : T[A]
  def node[A](a: A, l: T[A], r: T[A]) : T[A]
  def head[A](t: T[A]) : Option[A]
  def left[A](t: T[A]) : T[A]
  def right[A](t: T[A]) : T[A]
}
```

Programs for Testing: use Iter, Iterable

```scala
def sumElements[I[_]](xs: I[Int])(implicit IT: Iter[I]): Int = {
  IT.getValue(xs) match {
    case None => 0
    case Some(n) => n + sumElements(IT.getNext(xs)) }
}
def printElements[I[_],A](xs:I[A])(implicit IT: Iter[I]): Unit = {
  IT.getValue(xs) match {
    case None =>
    case Some(n) => {printIn(n); printElements(IT.getNext(xs))}}
}
def sumElements2[R[_]](xs: R[Int])(implicit ITR: Iterable[R]) =
  sumElements(ITR.iter(xs))(ITR.iterIF)

def printElements2[R[_],A](xs: R[A])(implicit ITR: Iterable[R]) =
  printElements(ITR.iter(xs))(ITR.iterIF)
```

Programs for Testing: use All

```scala
def testList[L[_] : Iter](implicit LI: ListIF[L]) {
  val l = LI.cons(3, LI.cons(5, LI.cons(2, LI.cons(1, LI.empty))))
  println(sumElements(l)) //sumElements(l)(listIter[Int])
  printElements(l) //printElements(l)(listIter[Int])
}

def testTree[T[_] : Iterable](implicit TI: TreeIF[T]) {
  val t = TI.node(3, TI.node(4, TI.empty, TI.empty),
                     TI.node(2, TI.empty, TI.empty))
  println(sumElements2(t))
  printElements2(t)
}
```

List: provide Iter, ListIF

```scala
implicit val listIter : Iter[List] =
  new Iter[List] {
    def getValue[A](a: List[A]) = a.headOption
    def getNext[A](a: List[A]) = a.tail
  }

implicit val listIF : ListIF[List] =
  new ListIF[List] {
    def empty[A]: List[A] = Nil
    def head[A](l: List[A]) : Option[A] = l.headOption
    def tail[A](l: List[A]) : List[A] = l.tail
    def cons[A](a: A, l: List[A]) = a :: l
    def append[A](l1: List[A], l2: List[A]) = l1 ::: l2
  }
```

MyTree: use Iter, ListIF, provide Iterable, TreeIF

```scala
sealed abstract class MyTree[A]
case class Empty[A]() extends MyTree[A]
case class Node[A](value: A, left: MyTree[A], right: MyTree[A])
  extends MyTree[A]

implicit def treeIterable[L[_] : Iter](implicit IF: ListIF[L]) =
  new Iterable[MyTree] {
    type I[A] = L[A]
    def iter[A](a: MyTree[A]): L[A] = a match {
      case Empty() => IF.empty
      case Node(v, left, right) =>
        IF.cons (v, IF.append(iter(left), iter(right)))    }
    val iterIF = implicitly[Iter[L]] }
```

MyTree: use Iter, ListIF, provide Iterable, TreeIF

```scala
implicit val treeIF : TreeIF[MyTree] =
  new TreeIF[MyTree] {
    def empty[A] = Empty()
    def node[A](a: A, l: MyTree[A], r: MyTree[A]) = Node(a,l,r)
    def head[A](t: MyTree[A]) = t match {
      case Empty() => None
      case Node(v,_,_) => Some(v)      }
    def left[A](t: MyTree[A]) = t match {
      case Empty() => t
      case Node(_,lt,_) => lt      }
    def right[A](t: MyTree[A]) = t match {
      case Empty() => t
      case Node(_,_,rt) => rt      }
  }
```

Linking Modules

testList[List]

testTree[MyTree]

Iter being Iterable

```scala
implicit def iterIterable[IT[_] : Iter] = new Iterable[IT]
{
  type I[A] = IT[A]
  def iter[A](a: I[A]) = a
  def iterIF = implicitly[Iter[I]]
}

val l = List(3,5,2,1)
sumElements2(l)
printElements2(l)
```

Example: Functor Specification

```scala
trait Functor[F[_]] {
  def map[A,B](f: A=>B)(x: F[A]) : F[B]
}

def compose[F[_],A,B,C](g: B=>C)(f: A=>B)(a: F[A])
                       (implicit FT: Functor[F]): F[C] =
  FT.map(g)(FT.map(f)(a))
```

Example: Functor Implementation

```scala
implicit val ListFunctor : Functor[List] = new Functor[List] {
  def map[A,B](f: A=>B)(x: List[A]) = x.map(f)
}
implicit val MyTreeFunctor : Functor[MyTree] = new Functor[MyTree] {
  def map[A,B](f: A=>B)(x: MyTree[A]) : MyTree[B] = x match {
    case Empty() => Empty()
    case Node(v,l,r) => Node(f(v),map(f)(l),map(f)(r)) }
}


compose((x:Int)=>x*x)((x:Int)=>x+x)(List(1,2,3))
val t : MyTree[Int] =
        Node(3,Node(4,Empty(),Empty()),Node(2,Empty(),Empty()))
compose((x:Int)=>x*x)((x:Int)=>x+x)(t)
```

Even Higher Kinds

```scala
// Iter: (* -> *) -> *
abstract class Iter[I[_]] {
  def getValue[A](a: I[A]) : Option[A]
  def getNext[A](a: I[A]) : I[A]
}

// Foo: ((* -> *) -> *) -> *
abstract class Foo[I[_[_]]] {
  def get : I[List]
}

def f(x: Foo[Iter]) : Iter[List] = x.get
```

Turning Type Classes into OO Classes

Interfaces

```scala
abstract class DataProcessor[D] {
  def input(d: D, s: String) : D
  def output(d: D) : String
}


abstract class DPFactory {
  def getTypes: String
  def makeDP(dptype: String) : ???
}


abstract class UserInteraction {
  def run(implicit factory: DPFactory) : Unit
}
```

How to return data with associated functions like OOP?

Turning Type Classes into OO Classes

```scala
import scala.language.higherKinds
import scala.language.implicitConversions

abstract class Box[S[_]] {
  type Data
  val d: Data
  val i: S[Data]
}

object Box {
  implicit def apply[D,S[_]](dd: D)(implicit ii: S[D]): Box[S] =
    new Box[S] {
      type Data = D
      val d = dd
      val i = ii
    }
}
```

Interfaces

```scala
abstract class DataProcessor[D] {
  def input(d: D, s: String) : D
  def output(d: D) : String
}

abstract class DPFactory {
  def getTypes: String
  def makeDP(dptype: String) : Box[DataProcessor]
}

abstract class UserInteraction {
  def run(implicit factory: DPFactory) : Unit
}
```

Data Processor

```scala
implicit val dpfactory = new DPFactory {
  def makeProc(init: Int, op: (Int,Int)=>Int): Box[DataProcessor] =
    Box(init)(
      new DataProcessor[Int] {
        def input(d: Int, s: String) = op (d, s.toInt)
        def output(d: Int) = d.toString()
      })

  def getTypes = "(sum/mult)"
  def makeDP(dptype: String) = {
    if (dptype == "sum")
      makeProc(0, (x,y) => x + y)
    else
      makeProc(1, (x,y)=> x * y)
  }
}
```

User Intraction

```scala
implicit val userInteraction = new UserInteraction {
  def getInputs[D](d: D)(implicit IO: DataProcessor[D]): D = {
    val d2 = IO.input(d, scala.io.StdIn.readLine("Input Data: "))
    val done = scala.io.StdIn.readLine("More inputs? [Y/N]: ")
    if (done.toLowerCase() == "n") d2
    else getInputs(d2)
  }
  def printOutputs[D](d: D)(implicit IO: DataProcessor[D]) = {
    println("The result of processing your inputs is:")
    println(IO.output(d))
  }
  def run(implicit factory: DPFactory) = {
    val dptype = scala.io.StdIn.readLine(
                "Input a processor type " + factory.getTypes + ": ")
    val dp = factory.makeDP(dptype)
    printOutputs(getInputs(dp.d)(dp.i))(dp.i)
  }
}
```

Linking

implicitly[UserInteraction].run

Heterogeneous List of Iter

```scala
abstract class Iter[I,A] {
  def getValue(i: I): Option[A]
  def getNext(i: I): I
}


def sumElements[I](xs: I)(implicit IT: Iter[I,Int]) : Int =
  IT.getValue(xs) match {
    case None => 0
    case Some(n) => n + sumElements(IT.getNext(xs))
  }


def sumElementsList(xs: List[Box2[Iter,Int]]) : Int =
  xs match {
    case Nil => 0
    case hd :: tl => sumElements(hd.d)(hd.i) + sumElementsList(tl)
  }
```

Turning Type Classes into OO Classes

```scala
import scala.language.higherKinds
import scala.language.implicitConversions

abstract class Box2[S[_,_],A] {
  type Data
  val d: Data
  val i: S[Data,A]
}


object Box2 {
  implicit def apply[S[_, _],D,A](dd: D)(implicit ii: S[D,A]):
  Box2[S,A] = new Box2[S,A] {
    type Data = D
    val d = dd
    val i = ii
  }
}
```

Test

```scala
implicit def listIter[A] : Iter[List[A], A] =
  new Iter[List[A],A] {
    def getValue(a: List[A]) = a.headOption
    def getNext(a: List[A]) = a.tail
  }


implicit def decIter : Iter[Int,Int] = new Iter[Int,Int]
{
  def getValue(i: Int) = if (i >= 0) Some(i) else None
  def getNext(i: Int) = i - 1
}


sumElementsList(List(
  100,
  List(1,2,3),
  10))
```

Iterable

```
// abstract class Iterable[R,I,A] {
//   def iter(a: R): I
//   def iterIF: Iter[I, A]
// }
abstract class Iterable[R,A] {
  def iter(a: R): Box2[Iter,A]
}


def sumElements2[R](xs: R)(implicit ITR: Iterable[R,Int]) = {
  val cs = ITR.iter(xs)
  sumElements(cs.d)(cs.i)
}


def printElements2[R,A](xs: R)(implicit ITR: Iterable[R,A]) = {
val cs = ITR.iter(xs)
  printElements(cs.d)(cs.i)
}
```

MyTree

```scala
sealed abstract class MyTree[A]
case class Empty[A]() extends MyTree[A]
case class Node[A](value: A, left: MyTree[A], right: MyTree[A])
  extends MyTree[A]

implicit def treeIterable[A] :
  Iterable[MyTree[A], A] = new Iterable[MyTree[A], A] {
  def iter(a: MyTree[A]) : Box2[Iter,A] = {
    def go(l: MyTree[A]) : List[A] =
      l match {
        case Empty() => Nil
        case Node(v, left, right) => v :: (go(left) ++ go(right)) }
    go(a) // Box2(go(a))(listIter[A])
  } }
val t : MyTree[Int] =
  Node(3,Node(4,Empty(),Empty()),Node(2,Empty(),Empty()))
sumElements2(t) //sumElements2(t)(treeIterable[Int])
printElements2(t) //printElements2(t)(treeIterable[Int])
```

Iter being Iterable

```scala
implicit def iterIterable[I,A](implicit IT: Iter[I,A]) :
  Iterable[I,A] = new Iterable[I,A] {
    def iter(a: I) = a // Box2(a)(IT)
  }


// val l = List(3,5,2,1)
sumElements2(l)
printElements2(l)
```

Stacking with Type Classes

IntStack Spec

```scala
abstract class Stack[S,A] {
  def empty : S
  def get(s: S): (A,S)
  def put(s: S)(x: A): S
}

def testStack[S](implicit stk: Stack[S,Int]) = {
  val s0 = stk.empty
  val s1 = stk.put(s0)(3)
  val s2 = stk.put(s1)(-2)
  val s3 = stk.put(s2)(4)
  val (v1,s4) = stk.get(s3)
  val (v2,s5) = stk.get(s4)
  (v1,v2)
}
```

Implementation using List

```scala
implicit def StackListInt : Stack[List[Int],Int] =
  new Stack[List[Int],Int] {
    val empty = List()
    def get(s: List[Int]) = (s.head, s.tail)
    def put(s: List[Int])(x: Int) = x :: s
  }
```

Modifying Traits

```
def IntStackWithPut[S](parent: Stack[S,Int],
                        newPut: (S,Int) => S) : Stack[S,Int] =
  new Stack[S,Int] {
    def empty = parent.empty
    def get(s: S) = parent.get(s)
    def put(s: S)(x: Int) = newPut(s,x)
  }

def Doubling[S](parent: Stack[S,Int]) : Stack[S,Int] =
  IntStackWithPut(parent, (s,x) => parent.put(s)(2 * x))

def Incrementing[S](parent: Stack[S,Int]) : Stack[S,Int] =
  IntStackWithPut(parent, (s,x) => parent.put(s)(x + 1))

def Filtering[S](parent: Stack[S,Int]) : Stack[S,Int] =
  IntStackWithPut(parent,
                   (s,x) => if (x >= 0) parent.put(s)(x) else s)
```

Linking

```
testStack(Filtering(Incrementing(Doubling(StackListInt))))
```

Implementation: Sorted Stack

```
def SortedStackListInt : Stack[List[Int],Int] =
  new Stack[List[Int],Int] {
    def empty = List()
    def get(s: List[Int]) : (Int,List[Int]) = (s.head, s.tail)
    def put(s: List[Int])(x: Int) : List[Int] = {
      def go(l: List[Int]) : List[Int] = l match {
        case Nil => x :: Nil
        case hd :: tl => if (x <= hd) x :: l else hd :: go(tl)
      }
      go(s)
    }
  }

testStack(Filtering(Incrementing(Doubling(SortedStackListInt))))
```

PART 4
Imperative Programming with Memory Updates

Mutable Variables

➤Mutable Variables
- Use "var" instead of "val" and "def"
- We can update the value stored in a variable.

```scala
class Main(i: Int) {
   var a = i
}

val m = new Main(10)
m.a   // 10
m.a = 20
m.a   // 20
m.a += 5   // m.a = m.a + 5
m.a   // 25
```

While loop

➢While loop

- Syntax: while (*cond*) *body*
  Executes *body* while *cond* holds.

- It is equivalent to:

```
def mywhile(cond: =>Boolean)(body: =>Unit) : Unit =
    if (cond) { body; mywhile(cond)(body) } else ()
```

➢Example

```
var i = 0

var sum = 0

while (i <= 100) { // mywhile (i <= 100) {
   sum += i
   i += 2
}
sum // 2550
```

For loop

➢For loop

- Syntax: `for (i <- ` *collection*`)` *body*
  Executes *body* for each `i` in *collection*.

- It is equivalent to:

```scala
def myfor[A](xs: Traversable[A])(f: A => Unit) : Unit =
  xs.foreach(f)
```

➢Example

```scala
var sum = 0
for (i <- 0 to 100 by 2) { // myfor (0 to 100 by 2) { i =>
  sum += i
}
sum // 2550
```

Additional Resources

➢UCSD CSE 130
- http://cseweb.ucsd.edu/classes/wi14/cse130-a/lectures/scala/00-crash.html
- http://cseweb.ucsd.edu/classes/wi14/cse130-a/lectures/scala/01-iterators.html

Thanks for your hard work!